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ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

Prepared by

Dr. Don L. Warner, P.E., C.P.G.
Rolla, Missouri

for the

American Petroleum Institute
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CONTENTS

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FIGURES

I. SUMMARY AND CONCLUSIONS

Many thousands of wells have been drilled and abandoned during the 130 year history of the U.S. petroleum industry. Regulations for plugging of such wells were nonexistent in the early days of the industry and have evolved, over the years, to their present effective level. Thus, an unknown but large number of abandoned wells exist that are unplugged or inadequately plugged by today's standards.

As a result of incidents in which abandoned wells have been implicated as sources of ground water contamination, such wells are often considered, without discrimination among them, to be potential pathways for contamination of an underground source of drinking water (USDW). Such contamination can result from interaquifer flow of natural formation water or by transmission of injected fluids from the injection reservoir to an USDW.

In fact, the relative contamination potential of such wells ranges from highly likely to impossible, depending on a complex set of geologic and hydrologic circumstances. The relative contamination potential of an abandoned well or wells in a particular geologic and hydrologic setting can be analyzed qualitatively by an understanding of the factors involved and can be quantitatively analyzed with available numerical computer models. An example of such a model analysis is given for a case where the abandoned well is judged to not be a potential source of contamination to an USDW, even in the presence of a nearby injection well.

It can be concluded that abandoned unplugged or improperly plugged wells may or may not pose a potential for contamination to underground sources of drinking water, depending on a complex set of geologic and hydrologic circumstances. Therefore, it seems reasonable that regulation of oil and gas industry activities should take into account the wide range of contamination potential of individual abandoned wells when establishing specific operating restrictions in their vicinity.

II. INTRODUCTION

During the 130 year history of the U.S. petroleum industry hundreds of thousands of oil and gas[1] exploration and production wells have been drilled, many of which are abandoned. For many years, effective requirements for the plugging of wells upon abandonment did not exist and, thus, an unknown but very large number of unplugged or inadequately plugged wells exists in the country. Such abandoned wells have been observed to be conduits by which

1. Under the Underground Injection Control regulatory programs of the U.S. EPA, petroleum industry injection wells are defined as Class II wells.

natural formation waters and, perhaps, injected fluids have migrated between subsurface formations (Figure 1) and in some cases, to the ground surface (Figure 2). This is a particular threat where injection wells are present that increase reservoir pressures and can induce such fluid movement as is shown in Figures 1 and 2.

As a result of such known or suspected incidents involving abandoned wells, some can be expected to believe that all abandoned wells pose a contamination potential to USDW's. This paper is intended to briefly outline the circumstances under which abandoned unplugged or improperly plugged wells may and, on the other hand, may not be a pathway for contamination of an USDW. The paper will show that the circumstances that determine the extent of hazard of an abandoned well are very complex and have, only recently, become subject to analysis by computer modeling. A case example of such modeling is given in which an abandoned well is analyzed and judged to not be a threat to an USDW.

III. GEOLOGY AND HYDROGEOLOGY OF OIL AND GAS PRODUCING REGIONS

A. General Geologic Frameworks

The vast majority of oil and gas production is from sequences of sedimentary rocks that occur in geologic basin areas and range in thickness from a few thousand to over 50,000 feet. Oil and gas wells that penetrate these sedimentary rocks range from several hundred to over 20,000 feet in total depth. Types of sedimentary rocks containing oil and gas include sand and sandstone, siltstone, shale, limestone, dolomite, salt, gypsum and, occasionally, other less common ones. Sand, sandstone, limestone and dolomite are commonly porous and permeable enough to act as oil and gas producing reservoir rocks whereas siltstone, shale salt and gypsum are more likely to act as cap rocks or confining beds.

The various sedimentary rock types occur in intercalated sequences, depending on the environment in which they are deposited and the nature of the supply of the depositional material. In the United States, particular geologic basins are characterized by the rock sequences that they contain. For example, the Texas-Louisiana Gulf coastal region contains principally interbedded sand-siltstone-shale, whereas various interior basins are dominated by carbonate (limestone and dolomite) rocks with occasional sandstones and shales. These consolidated to semiconsolidated oil and gas bearing rocks are from Cambrian to Tertiary in age.

In many areas, the sedimentary rocks described above are overlain by thin layers of unconsolidated gravels, sands, silts and clays of alluvial, glacial or other origin that are of Recent or Pleistocene age and are generally fresh-water bearing.

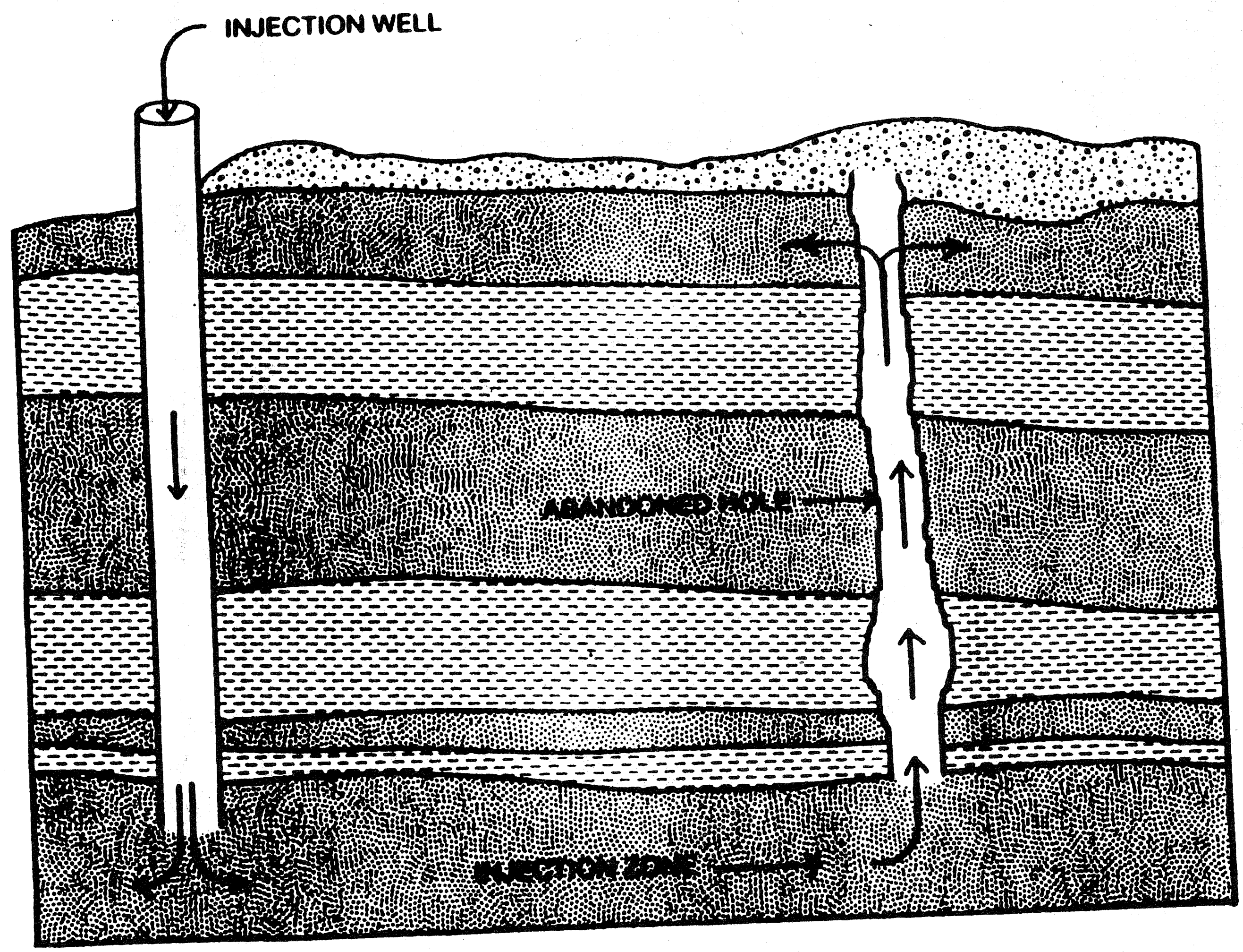


Figure 1 - Schematic diagram of interaquifer flow through the borehole of an abandoned well (Aller, 1984).

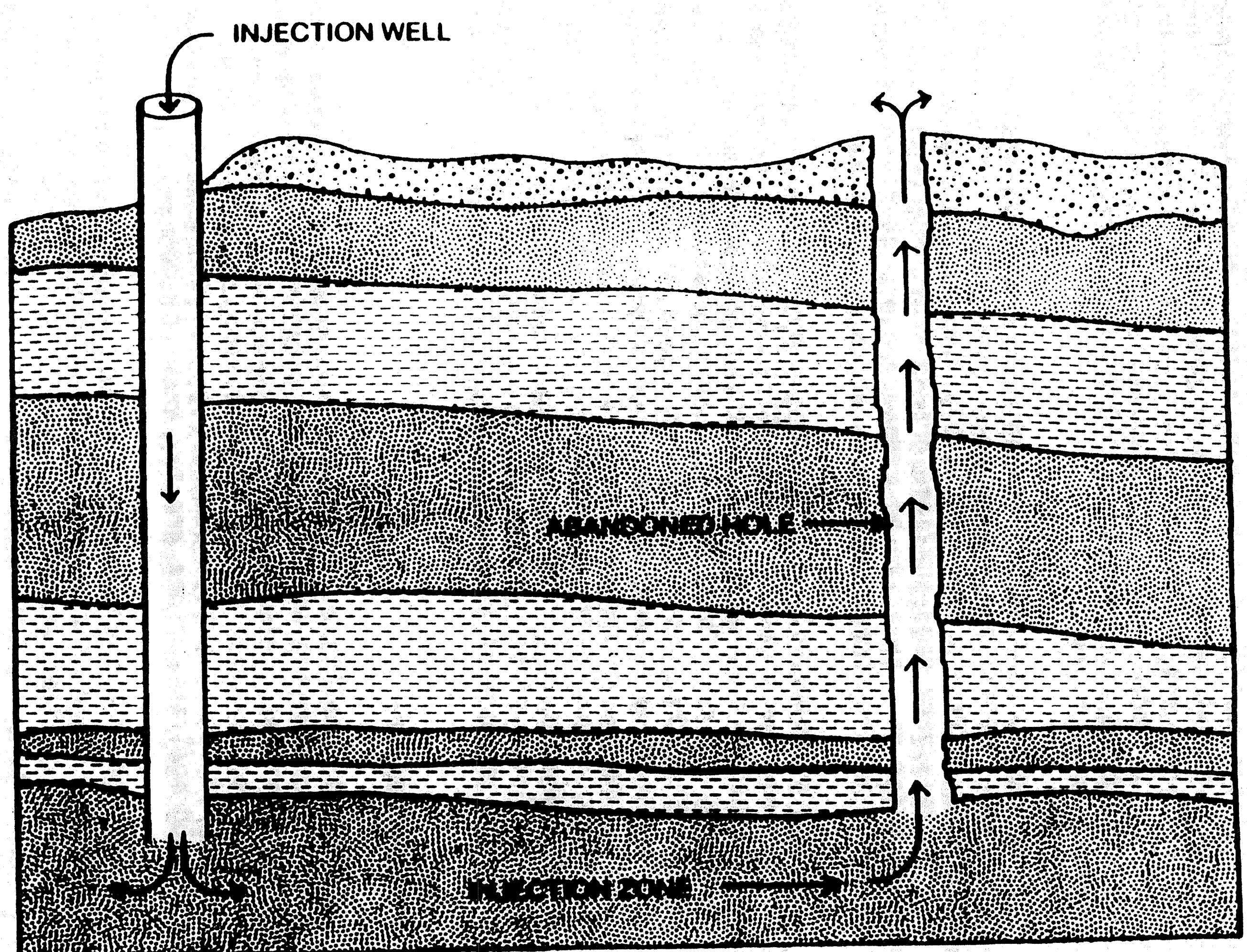


Figure 2 - Schematic diagram of flow to the ground surface through the borehole of an abandoned well (Aller, 1984).

B. Groundwater Occurrence and Movement

All soils and rocks contain water, in the subsurface. At depths of from a few feet to, at most, a few hundred feet, there is sufficient water present to completely saturate the soil or rock. The depth, at which saturation occurs is termed the ground-water table. Below that depth, all soil or rock is saturated and the contained water is termed ground water. Shallow ground water is often unconfined, that is, precipitation is able to infiltrate directly to the water table and recharge the water-containing aquifer. At greater depths, ground water becomes confined or semiconfined by the less permeable rocks in the sedimentary sequence. Oil and gas occurs and is accumulated in deep confined aquifers or reservoirs in very limited locations where structural and stratigraphic geologic conditions are favorable. All of the remaining subsurface rocks are entirely water filled.

Ground water circulates in response to the hydrologic cycle of precipitation, infiltration, recharge, ground water flow and discharge. Shallow ground water may flow relatively rapidly, as much as several feet per day, whereas very deep confined ground water may be almost stationary, flow rates being so slow as to be unmeasurable with the methodology available and in the time framework in which man operates.

In areas of relatively gentle topography, water in confined aquifers at the location of a single drilled well would rise in that well to nearly a common elevation, when adjusted for the differing density of the water in different aquifers. This condition is referred to as hydrostatic and simply means that there is little or no potential for the water to move vertically from one confined aquifer to another. In other cases, vertical equilibrium does not, naturally, exist and flow is occurring, though usually slowly, among confined aquifers. The status of the local ground water system, hydrostatic or not, is determined by drilling a borehole and measuring the level of the piezometric surface in each successively deeper aquifer by one or more of the various measurement methods available.

C. Groundwater Chemistry

The chemical quality of natural ground water is characterized by its content of the common cations, sodium, potassium, calcium and magnesium and the common anions; chloride, bicarbonate and sulfate and by the total dissolved solids comprised by these constituents. Fresh waters contain up to 1,000 mg/l of TDS, brackish waters 1,000-10,000 mg/l, saline waters 10,000-100,000 mg/l and brines greater than 100,000 mg/l of TDS.

The salinity or TDS content of a ground water is determined by its age and location and by the minerals that it has contacted during its lifetime. Young shallow waters tend to be low in TDS and deep old waters high in TDS. Often, a progressive increase in salinity occurs, with depth, in the aquifers intersected by a borehole in an oil producing area. Increased salinity also means increased density. Fresh water weighs

62.4 lb/ft^3 (has a specific gravity of 1.0) whereas a brine with a TDS content of 100,000 mg/l will weigh about 66.5 lb/ft^3 and have a specific gravity of 1.066. The hydrostatic pressure gradient of the fresh water would be 0.433 psi per foot of depth and of the brine would be 0.469 psi per foot of depth. An "average" hydrostatic gradient might be about 0.46 psi per foot of depth.

D. Hydrogeologic Parameters

To make quantitative assessments of ground water flow patterns and any consequent transport of contaminants in the subsurface, it is necessary to measure or estimate a number of hydrogeologic parameters or characteristics of the fluids and rocks involved. Fluid properties are density, viscosity compressibility and chemistry. Rock properties include porosity, permeablility, thickness and compressibility.

These fluid and rock properties are obtained by a variety of geologic, geophysical and engineering methods or, where not measured, are estimated. Calculations are then made with analytical equations or numerical models to analyze and predict patterns of subsurface water flow and possible associated ground water contamination.

IV. ENVIRONMENTAL IMPLICATIONS OF ABANDONED WELLS

When a borehole is drilled through a series of subsurface geologic formations that contain waters of differing chemical quality, it immediately becomes a potential pathway for movement of those waters among formations. This is one reason why wells are cased with steel casing and why cement is forced into the open area (annulus) between the casing and the wall of the borehole. It is the principal reason for the careful plugging of well bores with cement and drilling mud before well abandonment.

A. Properly Plugged and Abondoned Wells

In recent years, the Federal Government and the states have adopted increasingly stringent requirements for the methods and procedures for plugging and abandonment of oil and gas wells. It is assumed that, where wells have been plugged and abandoned under current procedures, the well bores are sealed and do not allow movement of fluids among subsurface formations and, thus, are not potential sources of ground water contamination.

B. Improperly Plugged and Abandoned Wells

During the early history of the oil and gas industry, the potential danger to usable ground water from abandoned unplugged or improperly plugged oil and gas wells was not recognized and many thousands of such wells were either not plugged at all or were inadequately plugged to prevent interformational water flow. In the earliest days of the oil and gas industry, scant or no recording requirements existed and the numbers and locations of many wells abandoned during that era are unknown.

As regulation improved, well permits were required and numbers and locations are on record. The details of plugging are, however, still often unknown and it must be assumed that effective plugs were often not emplaced. Modern wells are required to have permits for drilling and for abandonment and plugging methods and procedures are carefully supervised so that abandoned plugged wells are not a hazard to ground water.

From this brief history, it can be concluded that the potential for contamination to an USDW from abandoned wells is closely related to the era during which they were constructed, the hazard being from wells drilled prior to enactment of effective plugging and abandonment regulations. An important aspect of this conclusion is that the depth to which wells are drilled has steadily increased with time. Early wells were very shallow, often only a few hundred feet but seldom more than 2,000-3,000 feet in depth. Few wells today are less than 3,000 feet in depth. This means that most wells being drilled today will not be in direct conmmunication with many older unplugged or improperly plugged wells.

1. Exploration Wells vs. Development Wells

It is useful to distinguish among the types of wells drilled by the oil and gas industry when considering their possible contamination potential. Exploration wells are drilled outside of producing fields or are drilled to targets deeper than known production in producing fields. In either case, they are of lesser environmental concern than development wells drilled inside producing areas, since well density will be less and there is, therefore, less possiblity of interaction among wells that would lead to interformational fluid flow.

2. Variables Affecting Contamination Potential of an Abandoned Well

The variables that determine the contamination potential that an abandoned unplugged or improperly plugged well poses to underground sources of drinking water are many and complex. Let it first be said that some such abandoned wells do pose a threat to USDW's while many are believed not to, for reasons that will be examined.

a. Pressure Status of the Geologic Sequence Penetrated

In considering the potential environmental effects of unplugged or improperly plugged abandoned wells it is essential to characterized the pressure regimes that may exist in the formations penetrated by such wells. The possible detailed scenarios are too extensive for it to be practical to attempt to discuss them all. It was mentioned earlier that reservoirs or aquifers in a geologic sequence may naturally be under hydrostatic or normally pressured conditions or may be overpressured or underpressured relative to hydrostatic conditions. Considerable debate exists over the reasons for these varying natural pressure conditions but there is no question of their existence. Superimposed upon these natural reservoir or aquifer pressure conditions are the effects of petroleum production, groundwater pumpage, oilfield brine disposal by reinjection, secondary and enhanced oil recovery projects and other man-induced effects.

Whatever the original pressure status of a gelogic sequence of aquifers and reservoirs, petroleum production will lower the original pressure of the producing reservoir so that it will often be underpressured relative to the rest of the sequence. When petroleum production ceases, the reservoir will begin to return to its original natural pressure status. The rate of this pressure recovery depends upon the geologic and engineering reservoir characteristics but should require a time period comparable to that during when the reservoir was produced. The cycle of pressure depletion and recovery of an oil field will be affected by oilfield brine reinjection for pressure maintenance by waterflooding for secondary oil recovery and by enhanced-oil-recovery projects. Ground water pumpage will affect the pressures in drinking water aquifers similarly to production of petroleum reservoirs as described above.

The variety of possible flow patterns that can occur among aquifers and reservoirs with differing pressure conditions is, thus, very extensive and the local circumstances will have be examined in order to reach a conclusion concerning the threat of an abandoned well to an USDW. For example, there is no hazard of flow from a pressure-depleted petroleum reservoir to a normally pressured water-supply aquifer. In fact, flow would be into the pressure-depleted reservoir rather than from it. Even when reservoir pressure has recovered, no threat would exist in a normally pressured sequence. A hazard only exists when a saline-water bearing aquifer or reservoir is at a higher flow potential than an overlying fresh water aquifer connected with it by an unplugged or improperly plugged abandonded well. Even in that circumstance, movement of saline water into an USDW may not occur for reasons that will be described below.

b. Abandoned Well Flow Mechanics

Given the presence of an abandoned well that is improperly plugged or unplugged, is open to a geologic sequence of aquifers and which penetrates a petroleum producing reservoir or reservoirs, the analysis of the potential for flow of natural saline water or injected fluids into underground sources of drinking water is a complex but tractable problem. Among the variables of the problem are:

i. Flow potential status of all aquifers and reservoirs in the sequence penetrated by the abandoned well. This is discussed under a. above.

ii. Status or condition of the borehole of the abandoned well - Even though a well may have not been plugged or may have been inadequately plugged at abandonment, most boreholes will contain impediments to interaquifer fluid flow. These include drilling muds, partially effective cement or mud plugs, collapsed or sloughed formations, formations that have expanded into the borehole and, possibly, drilling equipment or well completion equipment lost in the hole. Only under unusual circumstances will abandoned wells not contain such flow impediments. A possible case of that type would be a cable-tool well drilled in a sequence of competent strata in which drilling mud was not used and in which no form of plug was ever employed. Such wells probably exist in early field areas in several geologic provinces but will, typically, be shallow and not in communication with present producing formations. Probably all rotary drilled wells will contain, at least, drilling mud as a flow impediment.

iii. Details of the operation of petroleum or water producing activities in formations intersected by the borehole - The effects of any injection and/or production wells that are completed in formations intersected by the boreholes of an abandoned well must be superimposed upon the flow gradients that exist under non-operational conditions. For example, if an abandoned well is bottomed in a petroleum reservoir that is undergoing waterflooding, the pressure effects of waterflood injection and production wells at the point where the abandoned well penetrates the reservoir must be determined so that the total differential pressure available to move fluids up the abandoned well is known. Effects of pumping from or injection into other aquifers must also be accounted for. For example, pumping from a fresh-water bearing aquifer would create a pressure decrease that would encourage fluid movement into that aquifer.

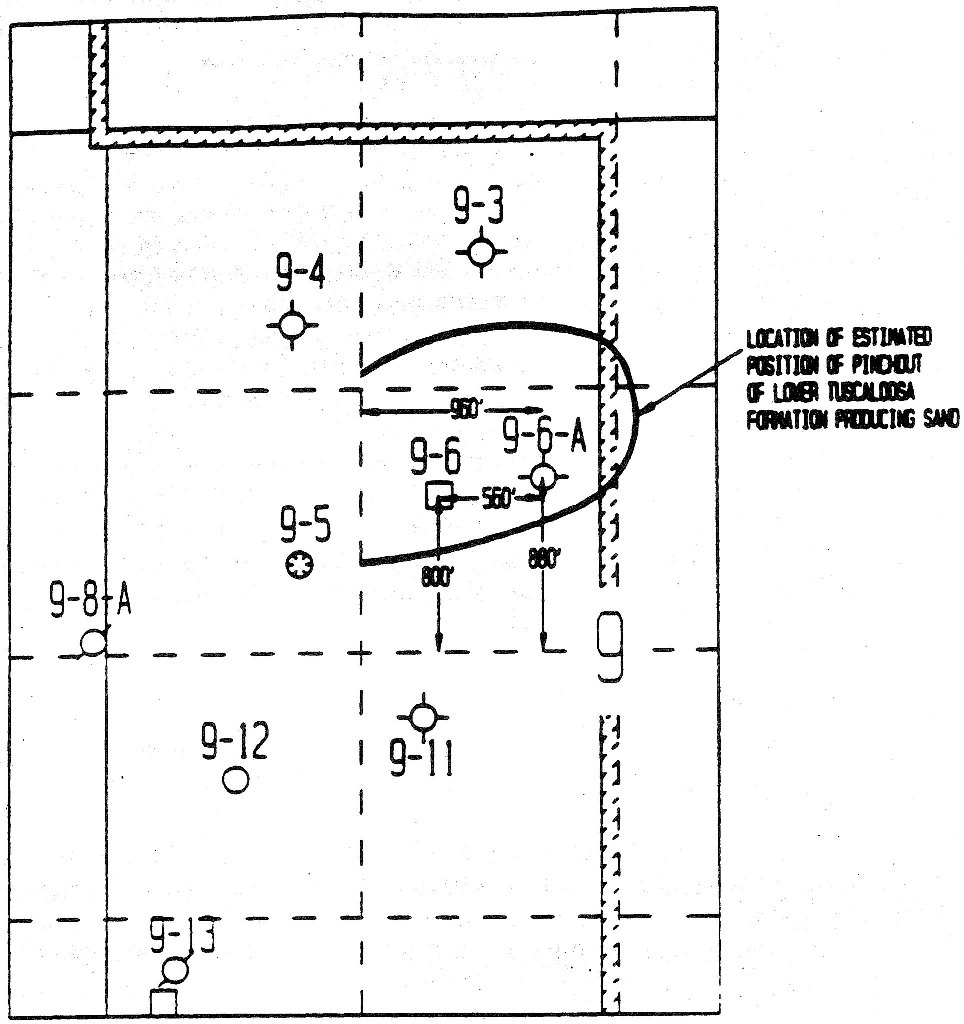
iv. Subsurface geologic conditions - Essential to determining the environmental hazard potential of an abandoned well is the subsurface geologic framework in the vicinity of the well. For example, if the abandoned well is drilled through formations that exhibit extreme lateral variability, the well may not be an effective pathway for fluid movement from an oil producing formation into a fresh water aquifer because the well may miss either the petroleum producing or water yielding units in the respective formations.

v. Engineering characteristics of all units in the geologic sequence and their contained fluids - The rate of flow and flow path that will be taken by formation waters or injected fluids in response to flow gradients that exist among formations in communication through an abandoned well will depend on the engineering properties of the formations and their contained fluids. Formation properties include porosity, permeability thickness and compressibility. Fluid properties include density, viscosity and compressibility. Both formation and fluid properties and the differential flow gradient are entere(into the appropriate analytical equations or numerical models in order to calculate flow paths and flow quantities. Such calculations are an accepted means of modeling subsurface flow problems and provide relatively practical means of evaluating hazard of an abandoned well.

V. CASE EXAMPLE

The case example that will be described is based on a recent unpublished study of the possible environmental effects of an abandoned well located near a proposed water injection well. The wells are located in an oilfield undergoing an enhanced oil recovery project in Mississippi. Figure 3 shows a portion of the oilfield with the two wells studied. Well 9-6 is the proposed water injection well. Well 9-6A is the abandoned well. The producing sand for the oilfield pinches out by facies change to the north, east and south of the two wells, as shown in Figure 3. Figure 4 shows a generalized stratigraphic column for the field. The Lower Tuscaloosa Sand is the producing sand for the field. It occurs at a depth of 10,490 feet in well 9- and is 26 feet thick. The base of the deepest underground source of drinkin(water occurs at a depth of 3100 feet, in sands of the Sparta Formation, whic| is about 700 feet thick.

The predicted hydraulic effects in abandoned well 9-6A resulting from proposed injection into Well 9-6 were studied with a numerical model, SWIFT III (Ward, 1987). SWIFT III is a revised and improved version of a code originally developed for the U.S. Geological Survey specifically for injecti well modeling. The original code and its successors have received extensive verification, validation and use. Figure 5 depicts the finite difference gr used in the simulations. Figure 6 is another representation of the grid showing the line of cross-section A-A', which is used to display the results of selected simulations.



XYZ FIELD
MISSISSIPPI

WELL STATUS
JULY 1987

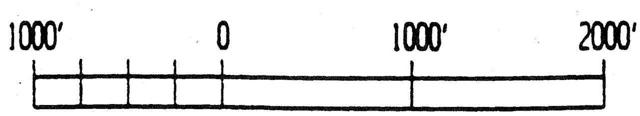
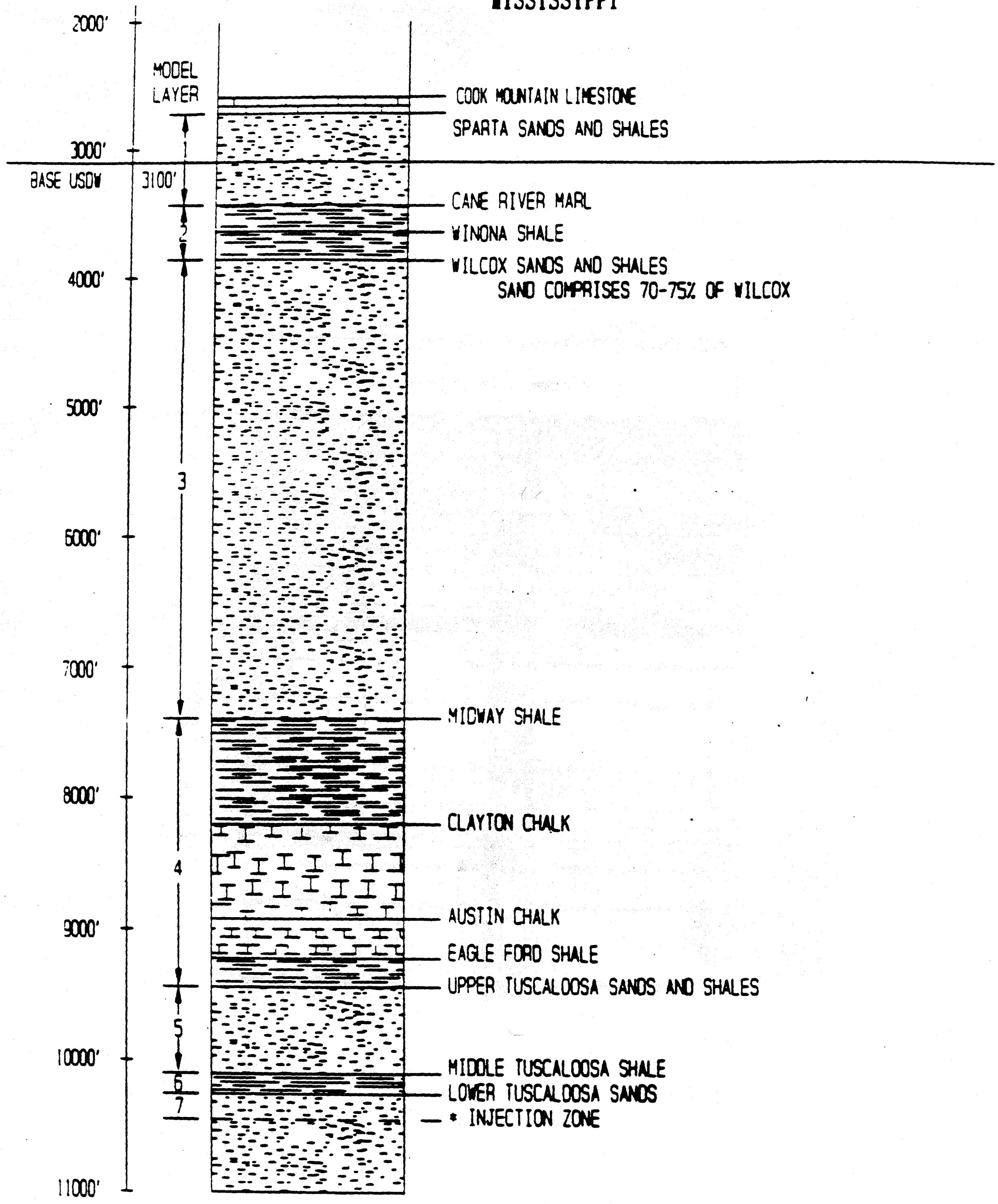


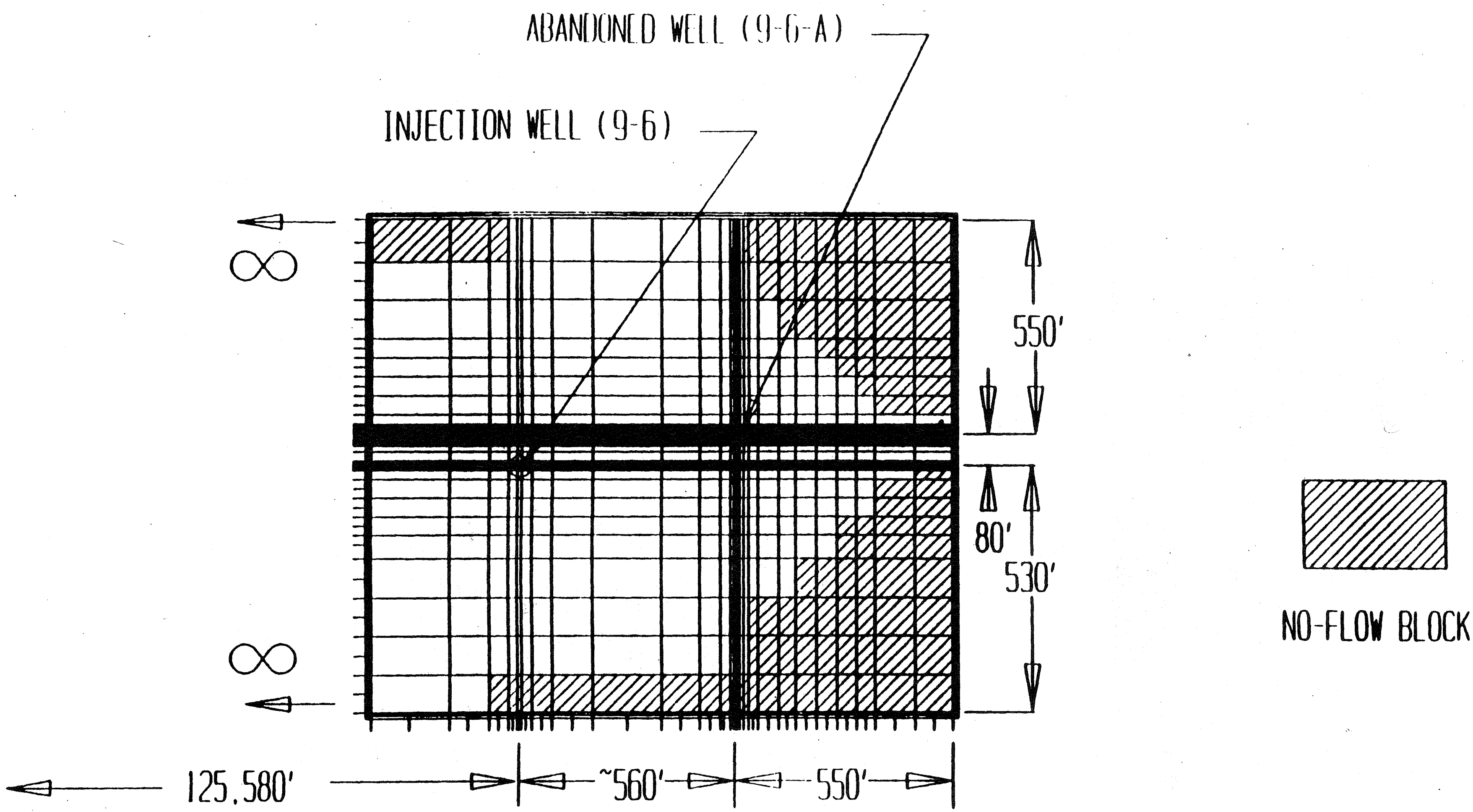
FIGURE 3

FIGURE 4

GENERALIZED STRATIGRAPHIC COLUMN

XYZ FIELD
MISSISSIPPI



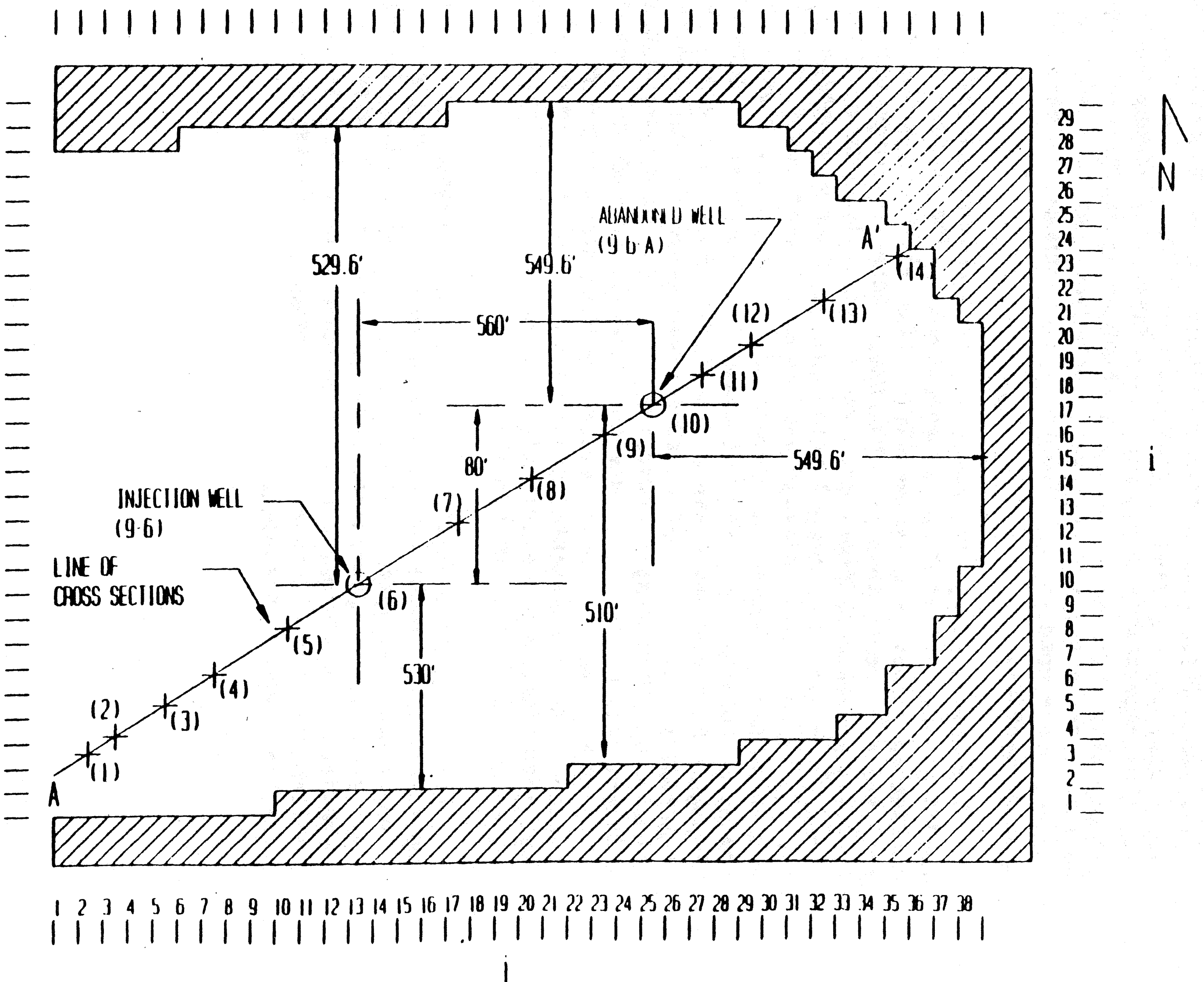


SCALED SIMULATION GRID

FIGURE 5

FIGURE 6

DETAIL OF THE SIMULATION GRID (7 LAYERS)



X AND Y SCALES ARE HIGHLY DISTORTED

The energy company that operates the oilfield under study provided the geologic and engineering parameters and operating schedule for Well 9-6, needed as input to the numerical model. It was assumed that the injection well would operate at near its maximum injection capacity, the constraint being the local fracture gradient of about 0.7 psi per foot of depth. The permeability of the Lower Tuscaloosa Sand was assumed to be a maximum probable 30 millidarcys and a minimum probable 2 millidarcys. The large range is the result of uncertainty concerning the effect of residual oil on the permeability to water. A total of about 20 simulation runs were made to calibrate the model and 10 final simulations were run to test various borehole and reservoir conditions. The results of representative simulations are discussed below.

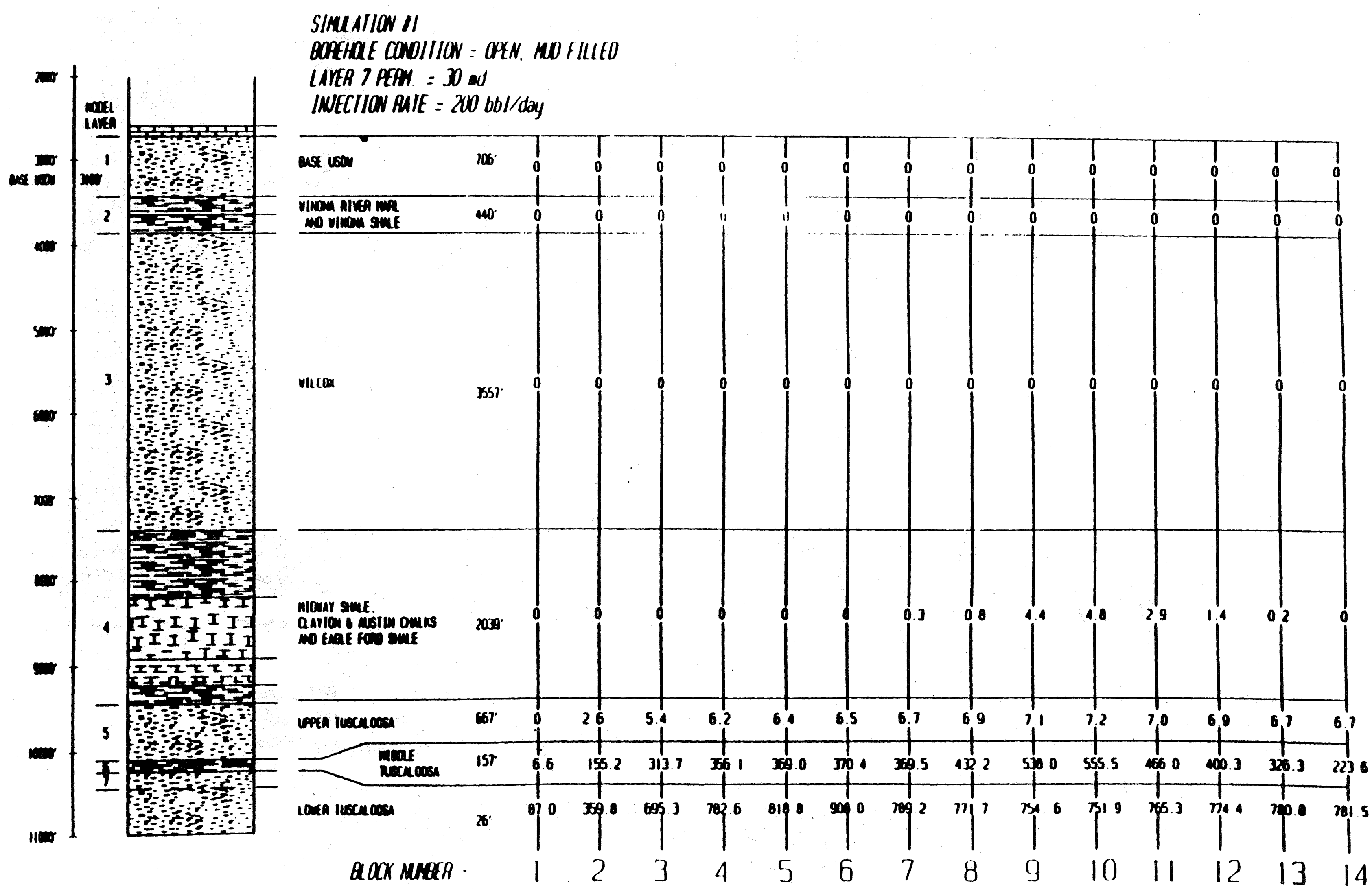
Figure 7 displays the results of a simulation in which the borehole of Well 9-6A was considered to be unplugged.[1] The Lower Tuscaloosa Sand was considered to have a permeability of 30 millidarcys and the injection rate in Well 9-6 considered to be 200 bbl/day. Reservoir pressure at the wellbore of Well 9-6 increased 908 psi over the 10-year simulation period and increased about 752 psi in the Lower Tuscaloosa Sand at the borehole of abandoned Well 9-6A. This pressure increase was transmitted through the Middle Tuscaloosa and through the borehole of Well 9-6A to the extent that up to a 7.2 psi pressure increase occurred in the Upper Tuscaloosa. Transmission of pressure through Well 9-6A also caused a buildup of up to 4.8 psi in Model Layer 4 but no pressure increase could be observed in the Wilcox Formation or units above the Wilcox. This result indicates that upward flow through abandoned Well 9-6A was insufficient to cause an observable pressure increase in the Wilcox and that no transmission of water to units above the Wilcox would be expected to occur. All subsequent simulations in which the permeability of the Lower Tuscaloosa Sand and the injection rate of Well 9-6 were proportionately varied, yielded the same result.

Cases were also studied where a plug composed of precipitated drilling mud solids was hypothesized to have developed. Figure 8 displays the results of one such simulation in which a plug of only 10-feet in length was considered to have developed in the interval of the Middle Tuscaloosa Formation. The 10-foot plug was assigned a permeability of 10^{-3} millidarcys. As shown in Figure 8, no observable pressure increase developed in layers above the Middle Tuscaloosa.

1. As has been discussed, it is believed that all rotary drilled boreholes will have some hydraulic resistance to flow. In this study, permeabilities of from about 40 to 4000 darcys were assigned to the borehole of Well 9-6A with no observable difference in the results.

FIGURE 7

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A' AFTER 10 YEARS OF INJECTION

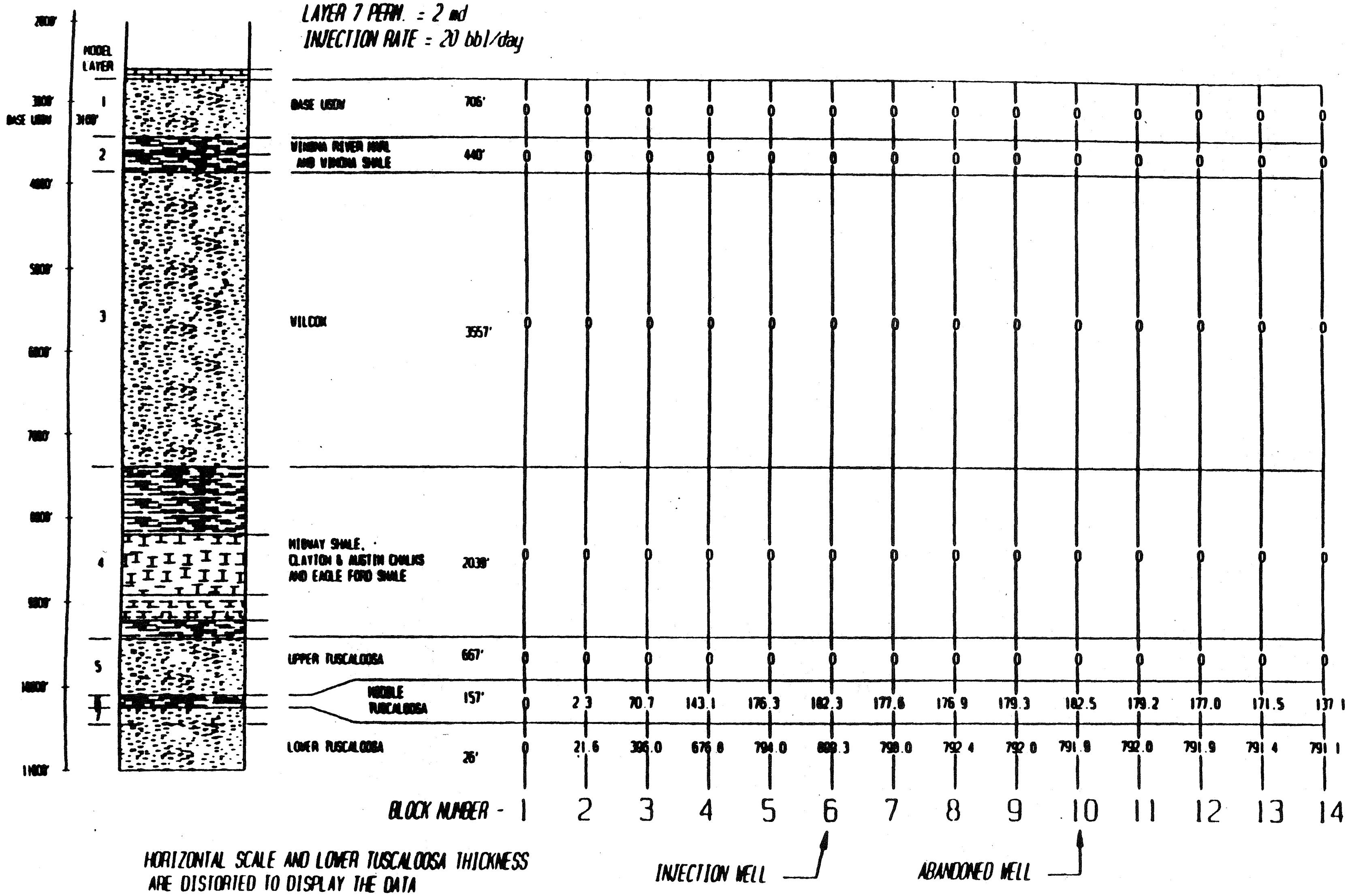


HORIZONTAL SCALE AND LOWER TUSCALOOSA THICKNESS ARE DISTORTED TO DISPLAY THE DATA

FIGURE 8

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A′ AFTER 10 YEARS OF INJECTION

SIMULATION #5
BOREHOLE CONDITION = 10 FT PLUG w/PERM. = 10^{-3} md
LAYER 7 PERM. = 2 md
INJECTION RATE = 20 bbl/day



The conclusion of the example discussed here is that modeling indicates that abandoned Well 9-6A poses no threat to underground sources of drinking water even if the nearby Well 9-6 were to be used for water injection at rates of up to 200 bbl/day over a period of 10 years. It can be expected that similar studies in other geologic and hydrologic situations would show that, in many cases, abandoned wells probably pose no potential for contamination of an USDW under any reasonable set of assumed circumstances. Thus, a differentiation among abandoned wells is needed to identify those locations in which such wells require the close attention of industry and regulatory agencies and those locations where the contamination potential is low to, perhaps, nonexistent.

VI. REFERENCES

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APPENDIX 4-14

Appendix 4-14

Factors That Can Cause Abandoned Wells to Leak as Verified by Case Histories from Class II Injection, Texas Railroad Commission Files (Clark et al., 1987)

INTERNATIONAL SYMPOSIUM ON SUBSURFACE INJECTION OF OILFIELD BRINES

Proceedings

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FACTORS THAT CAN CAUSE ABANDONED WELLS TO LEAK AS VERIFIED BY CASE HISTORIES FROM CLASS II INJECTION, TEXAS RAILROAD COMMISSION FILES

J. E. CLARK, M. R. HOWARD, D. K. SPARKS

E. I. DU PONT DE NEMOURS & CO., INC.

P. O. BOX 3269

BEAUMONT, TEXAS 77704

ABSTRACT

An abandoned well is a well where use has been permanently discontinued or is in disrepair such that it cannot be used for its intended purpose nor for observation purposes. A properly plugged well is a well where upward migration of fluids does not occur as a result of increased reservoir pressures.

Abandoned wells are possible sources of pollution to water supplies if fluids are allowed to migrate into Underground Sources of Drinking Water (USDW) from the over-pressured injection zone. Federal Underground Injection Control (UIC) regulations require the critical identification and evaluation of all abandoned wells in the Area of Review (AOR) during the permitting process.

Case histories from the Texas Railroad Commission files on leaking abandoned wells reportedly caused by Class II injection wells (salt water and enhanced recovery) were studied. Important factors have been identified from these case histories that can cause an improperly plugged abandoned well to leak due to overpressuring the injection zone. The factors include: 1) depth of the injection zone, 2) casing left in the borehole which is open to the injection zone, providing a direct path for upward fluid migration, 3) reservoir properties and flow rates, 4) drilling method, and 5) boreholes in "hard" rock which tend to remain open indefinitely, as opposed to boreholes in "soft" rock where expandable clays or sloughing shales close the borehole.

An important finding of this study was that wells drilled in unconsolidated (soft) rock, such as the Texas Gulf Coastal Plain experience natural borehole closure, which drastically reduces the potential for leakage from these abandoned wells. This study showed that the most likely pathway for leakage is a production well improperly abandoned with the production casing left open to the injection zone.

All abandoned wells in the AOR must be identified to satisfy Federal UIC regulations. Abandoned wells that are satisfactorily plugged are dismissed from further review, and remaining wells are considered for plugging or modeling to determine the maximum permissible injection pressure. The maximum injection pressure is set to prevent the hydraulic lift of the injected fluid or other non-native fluids into an overlying USDW from improperly plugged abandoned wells. During modeling it is important to consider the entire well field of surrounding injection or production wells which may affect the injection zone. From case studies of several Class II injection wells suspected of causing leakage through abandoned wells in Texas, we believe that operators can achieve responsible compliance through the use of historical records and available modeling techniques.

INTRODUCTION

Since 1859, when the first petroleum well was drilled in the United States, approximately three million oil and gas wells have been drilled and over two million have been abandoned (Anzzolin and Graham, 1984). According to 40 CFR 146, a well is considered abandoned if its use has been permanently discountinued or is in a state of disrepair such that it cannot be used for its intended purpose nor for observation purposes. Of particular concern to the Class II UIC program are improperly plugged wells that penetrate the injection zone or within 300 feet of the injection zone, because they have the potential for conveying fluid from the injection zone to an overlying Underground Source of Drinking Water (USDW).

Of the approximately 150,000 Class II (brine injection) wells operating in the United States (Fryberger and Tinlin, 1984), approximately 54,000 are in Texas (Roth, 1987). The State of Texas has recognized the need for proper plugging of abandoned wells since 1899 when the first regulations were passed. In 1919 the Texas

Railroad Commission (TRC) was given regulatory responsibility for proper well plugging. The TRC is also responsible for a program to remedy improperly abandoned wells where the operator is unknown or financially insolvent. Through this program approximately 1400 wells have been plugged since 1965 with state funds (Ross and Steed, 1984).

AREA OF REVIEW CONCEPT

The AOR is the main UIC requirement to protect an USDW against potential upward migration of fluid from boreholes that penetrate protective confining layers. Abandoned wells come under the current review process for a UIC permit. In Texas, the AOR encompasses the area within a 1/4-mile radius of the injection well. If unplugged wells are known to exist nearby, but outside the AOR, they may require reservoir simulations to determine the adequacy of the 1/4-mile radius (Engineering Enterprises, 1985).

This State UIC program requires that records of all artificial penetrations (boreholes that penetrate the confining/injection zone) be examined during the AOR to locate wells that are improperly abandoned. A properly completed or abandoned well is one where interformational movement of fluids will not occur as a result of an increased reservoir pressure.

We developed a protocol to identify and evaluate artificial penetrations in the AOR (Figure 1). All wells identified as being inadequately plugged must be modeled to verify that no upward migration will occur. If upward migration is possible, then one of the following steps must be taken before the injection well is allowed to operate:

1) Reenter and properly plug the potential problem well.

2) Lower the proposed injection rate to reduce the pressure (head) driving force.

3) Complete the injection well in a lower zone so that the abandoned well can tolerate a higher pressure without fluid migration.

4) Complete the injection well in a lower zone which the abandoned well does not penetrate.

5) Increase the density of the injection fluid to prevent upward migration.

6) Drill a monitor well next to the potential problem well to monitor possible upward fluid movement.

FACTORS RELATED TO LEAKAGE THROUGH IMPROPERLY ABANDONED BOREHOLES

Class II wells are generally constructed with surface casing cemented below freshwater aquifers, long-string casing perforated through the injection zone, and injection tubing to deliver brine to the subsurface. Figure 2 shows the construction of a Class II injection well and three improperly abandoned wells that provide potential fluid migration pathways. A leaking abandoned well can mean a leak at the surface or interformational flow of fluids which does not reach the surface (Figure 2). Injected fluids will move laterally through the injection zone and can migrate into an improperly plugged well. A discussion of important factors that relate to leaking abandoned wells follows.

For the purposes of the study, two rock types were identified: consolidated ("hard") rock and unconsolidated ("soft") rock. These two types are geologically distinct and their characteristics greatly influence the behavior of abandoned wells.

ROCK TYPES

Unconsolidated formations such as the geologically young Tertiary shales in the Texas Gulf Coastal Plain have hydration (expanding clays-smectities) and plastic properties which result in the natural closure of man-made boreholes (Johnston and Greene, 1979; Davis, 1986). Smectite exhibits a high amount of swelling when hydrated.

Non-expanding clays or illite swell much less on being wetted than expanding clays. Collins (1986) reported that shales penetrated by drilling fluids experience a significant water exchange due to an osmotic process which is dependent upon ionic activity of the mud and the brine in the shale. This water exchange can lead to swelling of the shale and sloughing into the borehole.

A change in mineralogy from smectite to illite occurs with increasing depth and temperature and is associated with squeezing water out of the clay lattice (Grim, 1968). This alteration is called clay diagenesis (See Figure 3). Powers (1967) found that when montmorillonite (smectite) is buried to a depth of approximately 3000 feet, most of the water is expelled from it, except for the last few bound layers that are along the basal layers between the unit layers of clay. At this depth, the effective porosity and permeability are essentially zero because all space is occupied by the solid layers of clay and the rigid water layers bound to the clay. In a laboratory experiment by Darley (1969) most of the free water in clays was squeezed out of the expanding clay members at a pressure of 2500 psi, approximately equivalent to 5000 feet of overburden.

Borehole closure by hydration occurs at depths less than 10,000 feet in the Gulf Coast. Alteration of smectite to illite (mixed-layer clay) begins at a depth of 6000 feet (Figure 3) and continues until a near total transition has occurred by a burial depth of approximately 10,000 feet in the Gulf Coastal Plain (Powers, 1967).

Below 14,000 feet in the Gulf Coast, there is no swelling component remaining in the illite (Burst, 1959).

Borehole closure by plastic flow is associated with high pore pressure shales being relieved of the overburden stress by penetration of the drill bit. This geopressured zone (plastic flow) occurs at approximately 10,000 feet in the Gulf Coastal Plain (Figure 3). Because the pore pressure and shale plasticity is abnormally high relative to the overburden strata, the shale is extruded into the borehole by plastic flow if the drilling fluid pressure (mud column weight) is less than the fluid pressure in the rock pores being drilled.

Drilling muds are generally conditioned to prevent borehole closure. If the mud breaks down or settles out, the borehole will seal itself by natural closure (Ammons, 1987). Johnston and Knape (1986) reported after interviewing several experienced drilling engineers that the geologically young and unconsolidated sediments of the Gulf Coast tend to slough and swell, and an uncased borehole will commonly squeeze shut within hours, resulting in natural borehole closure. According to Cheatham (1984), shale hydration has been one of the more significant causes of borehole instabilities in the past; however, improved drilling fluids in the last 20 years have provided better control of swelling shales. Therefore, old abandoned wells which typically did not have good drilling muds would have exhibited natural closure even more rapidly.

Reentering and plugging abandoned wells near Du Pont injection facilities in the Texas Gulf Coastal Plain has confirmed that the boreholes are closed by natural processes (Klotzman, 1986; Meers, 1987). Old abandoned boreholes have healed across shale sections to the extent that the reentering is like drilling a new hole. Natural borehole closure is also verified by day-to-day experience of field engineers who encounter difficulty in keeping boreholes open while drilling, running casing, and logging. Our experience in this area indicates that borehole closure while running casing can result in being stuck ("wall stuck") in the well and not able to bring circulation of fluids ("break circulation") to the surface. Generally a wiper trip is made (drill bit is run in the hole and the borehole is conditioned with mud) to keep the borehole open for logging if it needs to be left open for more than 24 hours.

Typically, dry holes drilled in the Gulf Coastal Plain have been abandoned with surface casing set and plugged, but without long string casing, thus providing ready opportunity for natural closure below surface casing.

Consolidated formations, such as in west Texas, are generally rigid ("hard rock") and lack the shale mineralogical properties that help the borehole to close by caving or sloughing (see Figure 4). Abandoned wells may remain open here indefinitely because the factors for natural closer are limited. Lost circulation zones are more common in consolidated rock areas where drilling fluids and cement may have been displaced from the borehole. Johnston and

Knape (1986) stated that abandoned wells in this region may remain open for many years, and reentering the boreholes for plugging may be done by merely washing down with a drill bit. Most reports of leaking abandoned wells or groundwater contamination have been reported as occurring in consolidated rocks (Johnston and Greene, 1979).

A major exception to the normal stability of the West Texas boreholes is exhibited in uncased sections of wells penetrating shale formations of the Triassic "red beds". These beds consist of water-sensitive clays which swell and slough in the borehole, causing well construction problems and total hole closure during and after well abandonment. This is typically below the base of the surface casing in a well where the long-string casing is absent or has been pulled for salvage prior to abandonment (Johnston and Knape, 1986).

DRILLING METHODS

The method used to drill a well can influence the potential for leakage after it is abandoned. Three dominant drilling methods examined were rotary mud, rotary air, and cable tool.

Rotary drilling with mud as the drilling fluid has been the preferred method, especially in the Gulf Coastal Plain, since its invention in 1901. It is almost impossible to drill shale with other techniques in coastal plain areas and keep the borehole open to advance the bit and casing.

The rotary mud rig uses a water-based drilling fluid (mainly a suspension of bentonite, a swelling clay), weighting material, and chemical additives as a medium to carry drill cuttings to the surface, control pressures encountered in underground formations, and lubricate the bit.

In most wells drilled prior to the 1930's, rotary drilling fluid was a mixture of water and the drill cuttings. This was called "native mud", derived from the clay formations penetrated by the drill bit. Water was continually added to thin native muds, and the minimum weight for these drilling fluids was probably not less than 9 lbs/gal (Johnston and Knape, 1986).

When a well reaches logging depth, the mud is conditioned to keep the borehole open prior to running geophysical logs (a practice since the 1930's). The density of mud left in the borehole can be determined from plugging records or from the geophysical log header.

Rotary drilled dry holes can be assumed to have been left full of mud as a **minimum** condition because there is no economic reason to recover the drilling mud prior to abandonment (Johnston and Knape, 1986). However, if the mud were recovered for another project, the borehole would be filled with a bentonite type mud. Totally removing the mud system from the borehole with the drill pipe on bottom of the well is taking an unnecessary risk of getting the drill pipe (salvagable material) stuck in the hole, because removing the mud can cause hole instability and caving.

Mud density, primarily used for well control while drilling, can also be used to prevent interformational fluid flow. Permeability of the mud left in the borehole is less than the surrounding productive formations and the pressure maintained by the mud column in the hole is high enough to prevent the displacement of the plugging material. Drilling fluid that is suitably conditioned after drilling can satisfy these requirements (Polk and Gray, 1984).

In plugging mineral exploration holes, Polk and Gray (1984) found that by increasing mud viscosity to 20 sec/quart, the exploration holes that were drilled were sealed with permeabilities less than 10^{-8} cm/sec. The sealing effectiveness of the mud conditioner treatment was confirmed by observations of surface hole intercepts made during the mining operations. This fact minimizes the chance of encountering a truly open conduit in an abandoned dry well which was rotary drilled using mud.

Cable tool drilling is sometimes used in consolidated rock formations, but it has not been used very much in unconsolidated rock regions for the past 50 years because caving sands and sloughing shales caused operating problems. If a well were drilled by cable tool or rotary air drilling methods, then the fluid in the hole is probably native water or brine. Generally, cable tool holes are hard to locate because the surface casing was never cemented and was removed after drilling.

MUD WEIGHT

The mud column provides a downward force, or higher hydrostatic head, than the fluids in formations encountered by the drill bit to maintain well control (keep the well from "blowing out"). This same mud column can keep the abandoned well bore from "breaking out" due to injection in other wells, if the formation pressure is not increased above the hydrostatic head of the mud column. Figure 5 is an example of pressure resistance of a static mud column exerted at different depths and mud weights. Figure 6 represents normal formation pressure at depth for two pressure gradients. Figure 7 represents pressure resistance differential based on the hydrostatic pressure resistance of the mud column minus the formation pressure, for several different cases. Formation pressure must be greater than the pressure resistance of the mud column to cause movement of fluids in the improperly plugged borehole. This is a conservative calculation because it assumes no credit for borehole closure, gel strength, or pressure required to break the mud cake gel at the borehole face.

High-density muds undergo density changes due to gravitional settling. In a field experiment, Cooke, et al (1983, 1984) made direct determinations of change in the density of bentonite mud left standing in the annular space where pressure transducers at various levels along the outer casing were located. The water-based mud weighted with barite to 11.0 lbs/gal was reduced to 9.1 lbs/gal in eleven months. The weight of natural and modern muds left in the borehole have a reported low range of 9 to 9.5 lbs/gal (Price, 1971; Johnston and Knape, 1986; Collins, 1986; Davis, 1986; and Alford, 1987). A 9 lbs/gal mud would be a conservative value to use in modeling calculations to predict upward migration in abandoned wells. This value of 9 lbs/gal would be valid for rotary mud-drilled dry holes and for cased holes with long string or production casing only if records indicate mud/cement left in the boreholes. Of course, if the records indicate lost circulation zones, or if casing is pulled from the borehole, the mud column cannot be assumed to fill the borehole.

GEL STRENGTH

A second mud parameter, gel strength (Gs), helps prevent upward fluid movement in a mud-filled borehole. Gel strength is the property which acts to suspend the drill cuttings in the static mud column when circulation stops. Drilling mud gels under static conditions as a function of the amount and type of clays in suspension, time, temperature, pressure, pH, and chemical agents in the mud system. The pressure required to displace the gelled mud can be significantly large.

Gel strength may be the main factor in preventing brine from migrating up abandoned wells from a fluid flow injection well driven by pressure build-up (Collins, 1986; Johnston and Knape, 1986). Collins (1986), in simple laboratory experiments (pipe with collars or shoulders to simulate different hole sizes and filled with bentonite mud) to test gel strength, demonstrated that mud gel and hole irregularities interacted to yield a large contribution (five-fold or more increase in gel strength) to sealing pressure and help prevent upward migration.

Gel strength is increased by flocculation which enhances clay particle contact. Several studies were conducted which showed that gel strength increases with time (Garrison, 1939; and Gray, et al., 1980) at borehole conditions. An increase in pH (Garrison, 1939) increases gel strength. High pressures in thousands of psi (Hiller, 1963) pressures generally much greater than those encountered in Class II injection wells, decrease gel strength. The gelling nature of mud has been observed and reported in replugging abandoned wells (Johnston and Knape, 1986).

Minimum gel strength for drilling muds has been reported as 20 to 25 lbs/100 ft^2 (Barker, 1981; Johnston and Knape, 1986; Davis, 1986; Collins, 1986; and Gurke, 1987) and would provide a considerable safety factor in modeling most situations. Figure 8 is a plot of gel strength and pressure resistance to prevent upward migration. The added pressure resistance for a well 5000 feet deep with a gel strength of 20 lbs/100 ft^2 and a 6-inch borehole would equal 50 psi.

DEPTH OF INJECTION ZONE

Injection zone depth is important because a shallower borehole will have a lower hydrostatic head (downward force) due to the shorter fluid column weight in the abandoned well. A longer column of fluid (deeper injection zone) can counterbalance more formational pressure buildup in the injection zone. Table 1 shows the hydrostatic mud pressure for 9.0 lbs/gal mud at depths from 1000 to 5000 feet. The mud column has a pressure differential resistance to initiate upward flow (hydrostatic mud pressure minus formation pressure) of 18 psi at 1000 feet, and 90 psi at 5000 feet.

CASING LEFT IN BOREHOLE

Special attention should be placed on abandoned wells with long-string or production casing remaining in the borehole and left open to the production/injection zone. Generally, if production casing is intact, then a mud-filled hole cannot be safely assumed, unless records indicate the presence of mud or cement at abandonment to counterbalance higher injection pressures.

If an operator abandons a depleted well or dry hole without proper plugging, then injected fluid from a Class II well (Figure 2, Well A) could enter the improperly abandoned well from the same production zone (Figure 2, Well D). Another potential avenue for upward migration exists if the well is cemented across only part of the well bore, and drilling mud was displaced ahead of the cement from the annular space between the casing and the open hole (Figure 2, Well B). If cement was not circulated to the surface, the annular space above the cemented portion would be filled with drilling mud. If driving pressures are high enough, fluids can enter the uncemented or mud annulus and migrate upward if not cemented above the injection/production zone.

The annular mud space provides resistance as in the mud-filled borehole to upward migration because of the increased hydrostatic head of the mud column and gel stength of the mud (Davis, 1986). In addition, in the Gulf Coastal Plain, shale can close around the casing and seal off the borehole.

RESERVOIR PROPERTIES

Transmissivity and injection rates are the main variables that control formation pressure buildup in an injection zone. Transmissivity is equal to permeability of the injection zone multiplied by the pay thickness (injection zone height). Figure 9 shows the relationship between pressure buildup and distance from the injection well for various transmissivities and injection rates. Higher disposal injection pressure buildups are related to zones of low transmissivity and higher flow rates. Because flow rates are important to formation pressure buildup, it is imperative to consider other nearby disposal and production operations utilizing the same injection zone when determining the potential for leakage through abandoned wells.

MODELING UPWARD MIGRATION

Well-established, conservative, engineering models are available for computing the pressure at which upward migration will begin. The formation pressure necessary to initiate upward flow (Pf) through an abandoned well is determined first by calculating the pressure exerted by the well's mud column and then adding the pressure for gel strength (note that no additional credit is taken for borehole closure resulting from shale hydration or the plastic nature of abnormal pressured shales). Second, the formation pressure prior to injection (Po) is subtracted from Pf. This difference (Pf-Po) represents the injection formation pressure buildup which must occur at an abandoned well to initiate upward flow. This difference is the key for limiting the maximum permissible pressure increase in an injection formation at the location of an improperly plugged abandoned well. An equation developed by Barker (1981) to calculate the pressure resistance in an improperly abandoned well is as follows:

$$Pf = Pt + 0.052*p*H + (0.00333*Gs*H/ Dw) \qquad (1)$$

where : Pf = pressure required in the formation to initiate upward flow in an abandoned borehole (psi)

Pt = surface well pressure (psi)

p = density of mud (lbs/gal)

H = height of mud column (feet)

Gs = Gel strength of mud (lbs/100 ft^2)

Dw = maximum diameter of well bore (inches)

Davis (1986) reported an equation to calculate the opposing forces (mud hydrostatic head and gel strength) that act in resistance to upward fluid migration along a uncemented/mud casing annulus if not cemented above an injection or production zone:

$$Pf = Pt + 0.052*p*H + (0.00333*Gs*H/ Dw-Dc) \qquad (2)$$

where : Pf, Pt, p, H, Gs, and Dw are defined as in equation 1 and

Dc = outside diameter of casing (inches)

The AOR for an injection well is dependent upon the following variables:

1. unit weight of mud plug, gel strength, and borehole diameter,

2. reservoir properties: permeability (k) and pay zone (effective injection zone) thickness(H),

3. injection rates (Q),

4. injection or production operations utilizing the same injection zone,

5. initial reservoir pressure and surface pressure,

6. depth of injection zone,

7. injection and formation fluid properties.

When pressure modeling calculations indicate that injection well operations are sufficient to cause fluid migration in an abandoned well, one of the alternatives previously discussed under AOR must be pursued.

Figure 10 shows cross-section modeling calculations for a reservoir and indicates that with a 9 lbs/gal mud at 5000 feet, the area of review for abandoned rotary drilled dry wells would be less than 1000 feet from the injection well. Figure 11 is a plan view for the above modeling calculations.

CASE HISTORIES FOR LEAKING ABANDONED WELLS IN TEXAS

Agency Information Consultants, Inc. (AIC) of Austin, Texas has examined records on file with the Texas Railroad Commission (TRC) for pollution problems associated with abandoned wells in the following cases: 1) significant problem leaking abandoned wells in Texas cited by EPA (1975), (AIC, 1987a), 2) proper plugging hearings from selected counties along the Texas Gulf Coast (unconsolidated rock areas) to determine pollution problems in connection with the upward migration of fluids in improperly abandoned wells (AIC, 1987b), and 3) proper plugging hearings for fluid migration from improperly plugged wells in unconsolidated (TRC Districts 2, 3, and 4) and consolidated rock areas (TRC Districts 7-B, 7-C and 9) (AIC, 1987c).

CASE 1

The TRC gained authority and funds in 1967 to plug those wells causing a problem or presenting a potential pollution threat. EPA (1975) found approximately 830 wells that were plugged from 1967 to 1974 and identified approximately twenty-eight leaking, abandoned wells that were significant problems and reportedly caused by Class II injection wells (Figure 12, location map). These wells were found in a review of the TRC files on unplugged or improperly plugged wells that have been plugged by State authority. AIC (1987a) studied these 28 problem wells.

The AIC study identified the following as important factors that contribute to the potential for upward migration due to injection operations in the unconsolidated rock areas: 1) long-string casing left in the borehole and left open to the production or injection zone, and 2) significantly overpressured injection zones because of the low reservoir transmissivity.

Out of 28 problem wells, only 4 leaking abandoned wells were from the unconsolidated rock area (Figure 12). Three improperly abandoned wells in the unconsolidated rock region had production casing set and left open to the injection zone, providing a direct pathway to the surface and eliminating possibilites for borehole closure. In one of these wells, a cause-and-effect relationship was shown when a suspect injection well reduced its flow by two-thirds and another suspect well was shut in, the problem well stopped leaking.

The fourth well cited in the unconsolidated rock area was drilled to a total depth of 1395 feet, abandoned with 21 feet of surface pipe in the borehole and filled with heavy mud. The well suspected of causing the problem injected between 1810 to 1900 feet, or 400 feet below the depth of the leaking well. Thus, this suspect well is not likely to have been the cause of the leaking well. The most likely source of salt water for the abandoned well is the fact that fresh groundwater at this location is very shallow (less than 100 feet). When the leaking well was entered to stop the leak, "A partial obstruction was encountered at approximately 20 to 25 feet and it was found that a solid obstruction of clay and shale was encountered at approximately 50 feet. It is obvious that this obstruction will have to be drilled out rather than washed out in order to properly plug the well" (Eikel, 1969). This record on the attempt at reentering the abandoned well confirms that borehole closure can occur in unconsolidated formations.

In summary, improperly plugged abandoned wells in unconsolidated formations with long-string casing left open to the injection interval may have only mud and mud gel strength or formation brine to withstand pressure buildup. Thus, depth of injection is critical in these cases. It is important to review the records of all production wells within the AOR because they are commonly abandoned with casing intact and they have the greatest potential for upward migration.

In 21 of 24 cases in the consolidated rock area, leaking abandoned wells were again due primarily to injection by the suspect wells into the same interval to which the leaking wells had been open; but, it was through the production casing or the open borehole.

In the other three cases, AIC (1987a) could not find an injection well after searching a radius of 1.5 miles for well No. 25. In addition, the abandoned well was not leaking salt water but was identified as a well that was not properly plugged. A second leaking well was drilled to a depth of 4156 feet in consolidated formations and abandoned with 112 feet of surface casing in the hole with 75 sacks of cement and heavy mud. An injection well approximately 3/4 mile away (injection zone 518 to 535 feet) was suspected of causing the leak; however, when the injection well was shut down for a week, there was no change in the leaking well.

Thus, the suspect well was probably not the cause of the leakage. Additionally, the sand used for injection pinches out in the direction of the leaking well (Krusekopy, 1970). Lack of sand continuity prohibits lateral fluid migration. Thus, the suspect well was probably not the cause of this leakage. The third leaking well that did not fit the same zone as the suspect well was drilled to a total depth of 4,050 feet in consolidated formations and abandoned with 101 feet of surface casing in the hole and filled with mud. An injection well approximately 1700 feet away was suspected of causing the problem. This injection well was disposing of salt water through the annulus between 354 and 2302 feet. Modeling the suspect well based on the following limited reservoir parameters and sensitivity analysis:

where, Q (flow rate) = 110 bpd

H (pay zone) = 35 feet

p (injection pressure wellhead) = 175 psi

r (radius from well) = 1700 feet

indicated that pressure buildup due to injection was approximately 50 psi at the 530 foot depth injection zone. Assuming 9 lbs/gal mud in the abandoned borehole, the borehole can only support 10 psi buildup before fluid migrates upward (Figure 13, Case No. 3).

In all cases where there was sufficent reservoir data available to model pressure buildup at the leaking abandoned well, the reservoir pressure buildup exceeded the calculated pressure resistance for 9 and 10 lbs/gal mud systems (Figure 13).

In nearly all 28 cases cited by EPA (1975), AIC (1987a) found that records pertaining to cement and/or mud plugs in the leaking wells were inadequate, incomplete, or non-existent. Plugging with mud was more common than plugging with cement, but in either case, details on the mud weight ("heavy") and cement (amount and location of plugs) are usually not given. If this information is unavailable, then conservative values should be used in modeling (9 lbs/gal mud and no cement).

Two other important mechanisms that are related to reservoir modeling include well depth and distance from leaking well to suspect injection well. Figure 14 shows that the average depth for a leaking well in this case study is less than 2500 feet. Figure 15 shows that the maximum reported distance from a leaking well to a suspect Class II injection well is less than 6000 feet and the average is less than 2000 feet. This is consistent with reservoir modeling where greater formation pressure buildup is associated closer to the injection well.

CASE 2

A second study also conducted by AIC (1987b) involved the examination of proper plug hearing files in selected Gulf Coast counties. Proper plug hearings are called by the TRC "when it comes to their attention that a well has been abandoned or is not being operated and is causing or likely to cause pollution to freshwater above or below the below the ground or if gas or oil is escaping from the well, the commission shall determine at a hearing, after due notice, whether or not the well was properly plugged." These hearings are called under Statewide Rule 14 (b) (2) of the "Texas Statewide Rules For Oil, Gas, and Geothermal Operations."

This study was undertaken to determine the magnitude and mechanisms of pollution problems associated with improperly abandoned wells in unconsolidated sediments. From six selected counties along the Gulf Coastal Plain (Figure 16), 2531 oil and gas fields were examined. From these fields, 171 proper plug hearing orders were identified, only three involved actual leakage incidents of which only two were directly related to an injection well (Figure 17). These three pollution incidents were examined to verify the factors that caused the abandoned wells to leak.

Pollution incident No. 1 consisted of three wells on one lease that were in violation of proper plugging. Subsequent field investigations by the TRC revealed that surface pollution existed but was not the result of upward migrating fluids. Oil found in a pit near one well was leaking from a 250-barrel tank. Operator negligence was cited.

Pollution incidents Nos. 2 and 3 were the result of upward migration of fluids due to subsurface injection of Class II wells in San

Patricio County. Incident No. 2 involved an improperly abandoned production well leaking oil to the surface. This well had been drilled to 2590 feet. The well was abandoned with 885 feet of 8-5/8 inch surface casing, 2444 feet of 5-1/2 inch casing, and 2316 feet of 2-inch production tubing in the hole. The 5-1/2 inch casing was plugged back to 2345 feet and perforations were noted from 2446 to 2590 feet. The 2-inch tubing was cemented to the surface and mud-laden fluid was pumped into the well along with a 25 sack-cement plug (set at an unknown depth).

A suspect injection well was located approximately 2550 feet from the leaking well. This suspect well was probably not a likely cause of the pollution because its injection interval (5128 to 5132 feet) is far below the producing interval (2446 to 2590 feet). In addition, the leaking well never penetrated the injection interval. Oil migration has probably been the result of natural fluid migration from the production zone through the improperly abandoned production well.

Pollution incident No. 3 involved another improperly abandoned production well, cited for leaking oil and water to the surface from the thread of a "home-made" cap on the 5-1/2 inch casing. The well was abandoned with 210 feet of 8-5/8 inch surface casing, 1358 feet of 5-1/2 inch production casing, and 1355 feet of 2-inch tubing in the hole. No records of cement were found on this well indicating that it was ever plugged. The well was completed from 1331 to 1337 feet. A suspect injection well was located approximately 1300 feet away and the injection interval was from 1110 to 1155 feet. The suspect well was permitted to operate at an average of 300 bbl/day with maximum surface pressure of 30 psi.

Both pollution incidents Nos. 2 and 3 involved actual upward migration of fluids and had protection/production strings left in the hole, eliminating any possibility of borehole closure.

It is important to note that out of 2531 fields examined (the number of abandoned wells may exceed the number of fields by a factor of ten) along the Gulf Coast, only two leakage incidents were found. This case study confirmed that the number of pollution problems in the unconsolidated rock areas is small and indicates that natural borehole closure is an important mechanism in eliminating upward fluid migration.

CASE 3

To enhance our understanding and defend the conclusions of the second study, a third study was conducted of proper plug hearings for pollution incidents in "hard" and "soft" regions in Texas (AIC, 1987c). TRC Districts 7-B, 7-C, and 9 were selected as the "hard rock" area and Districts 2, 3, and 4 comprised the "soft rock" area (Figure 18). Districts were chosen primarily for their rock environment and large number of oil and gas fields (i.e., production wells).

According to Anzzolin and Graham (1984, citing A. D. Little), 95% of all production wells and 78% of all abandoned wells (Anzzolin and Graham, 1984) fall within the AOR of Class II injection operations. Accordingly, because each district contains a substantial number of oil and gas fields, we can assume that a significant number of Class II wells exist in each region studied. The study concluded that pollution incidents resulting from Class II injection operations in "hard rock" areas outnumber those cited in "soft rock" areas by a factor of 10. Our conclusions are explained in the following paragraphs.

Proper plug hearing files for 12,461 oil and gas fields in the "consolidated rock" area were studied for pollution incidents (AIC, 1987c). Seven hundred and ninety (790) hearing files were located, and further examination of these files found that 112 hearings were called as the result of fluid migration from improperly abandoned wells (Figure 19).

On the other hand, hearing files for 34,512 oil and gas fields in the unconsolidated area were studied for leakage incidents. Six hundred, seventy-four (674) hearings were found and only 16 indicated fluid migration. Nearly three times as many fields were examined in unconsolidated rock areas as compared to consolidated rock areas, but only 13% (16) of the 128 proper plug hearings from both areas resulted from upward fluid migration in unconsolidated rock.

The 16 unconsolidated rock pollution incidents were studied to determine the factors which caused the abandoned wells to leak. Fourteen of the pollution incidents involved wells abandoned with production casing left in the hole; two pollution incidents had incomplete or nonexistent records.

It is important to note that all sixteen unconsolidated rock incidents (leaking wells) were once production wells, and most, if not all, were completed or abandoned with production casing intact. In turn, by improper cementing across production intervals, improper abandonment, or both, these wells were left open to upward migrating fluids. Thus, natural borehole closure, common in the Gulf Coastal Plain or unconsolidated rock areas, was restricted because of production casing left open to the injection zone.

Regarding the 112 pollution incidents in "hard rock" regions, AIC (1987c) noted that the producing zones were much shallower than in "soft rock" areas. Abandoned wells in "hard rock" areas would tend to have smaller hydrostatic heads due to the shorter static mud column. Thus, pressure differentials between injection or production intervals and static mud columns are small and more likely to allow upward fluid migration than deeper injection or production zones in "soft rock". "Hard rock" areas accounted for 87% of the total 128 leakage incidents resulting from upward fluid migration.

CONCLUSIONS

Case studies of Class II injection wells from the Texas Railroad Commission files showed that only a small number of pollution problems from leaking abandoned wells are associated with the Texas Gulf Coastal Plain. These studies also documented natural borehole closure as an important mechanism in preventing upward fluid migration in the unconsolidated rock of the Texas Gulf Coastal Plain.

The most important factors providing potential for upward fluid migration due to injection operations in the unconsolidated rock regions are: 1) production wells which had protection or production casings left in the hole left open to the injection zone, eliminating any possibility of borehole closure; and 2) significantly overpressurized injection zones because of low reservoir transmissivity.

The case studies for west Texas (consolidated rock) indicate a higher percentage of pollution incidents resulting from improperly abandoned wells. The important factors relating to upward migration are: 1) boreholes abandoned with or without casing remaining open to the injection zone, 2) significantly overpressurized injection zones because of low transmissivity, and 3) shallower production or injection zones resulting in shorter static mud columns to counterbalance increased formation pressure.

This study of case histories has shown that all of the leaking abandoned wells could have been identified as potential problem wells. Preventive measures could have been taken prior to injection operation. We believe operators can achieve responsible compliance through the use of historical records and reservoir modeling to conduct injection operations in a manner that protects the environment.

TABLE 1

MUD WEIGHT PRESSURE RESISTANCE

Assuming 9.0 lbs/gal mud and formation pressure gradient of 0.45 psi/ft:

Depth (ft)	Hydrostatic mud pressure (psi)	Formation pressure (psi)	Pressure differential (psi)
1000	468	450	18
2000	936	900	36
3000	1404	1350	54
4000	1872	1800	72
5000	2340	2250	90

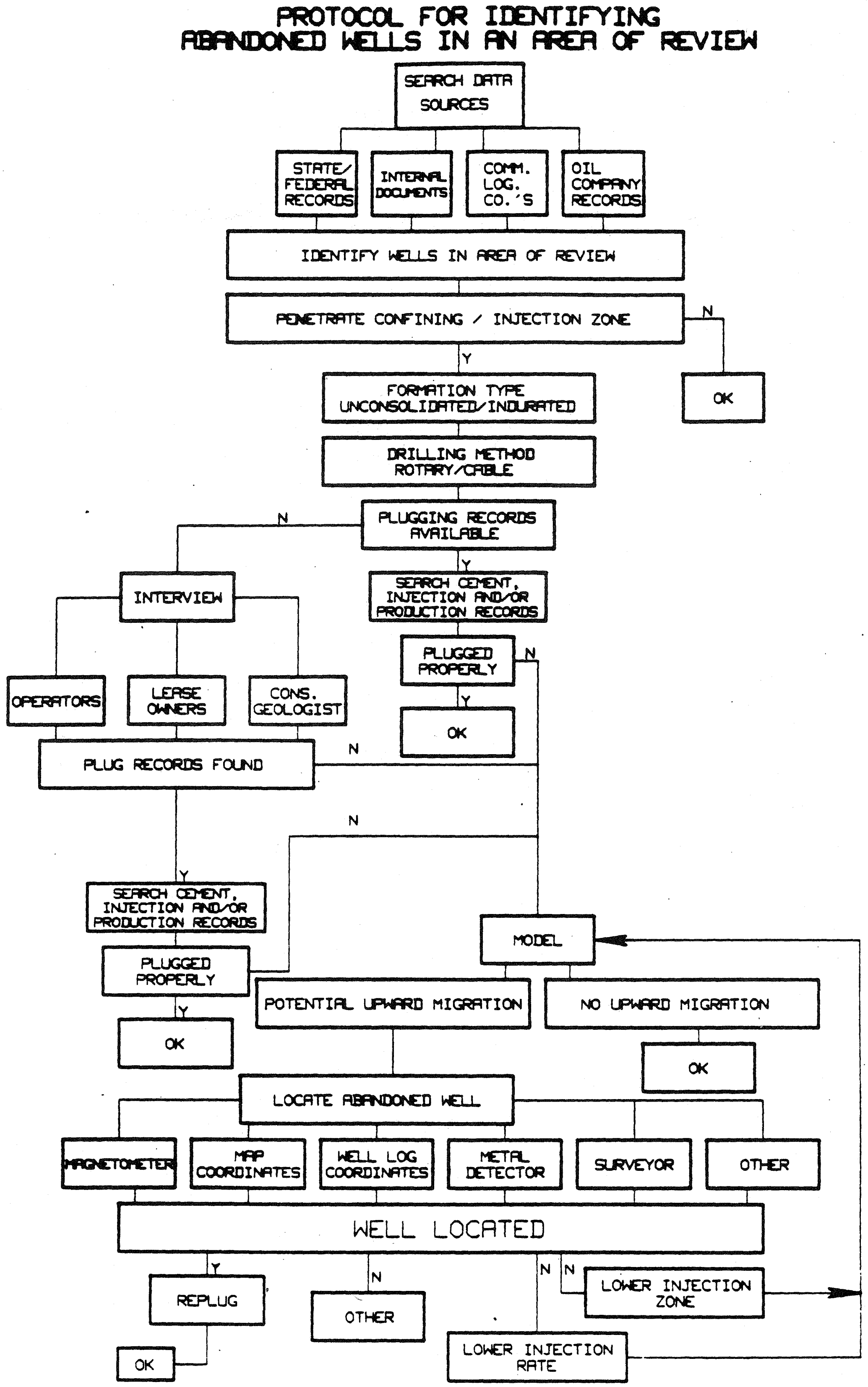
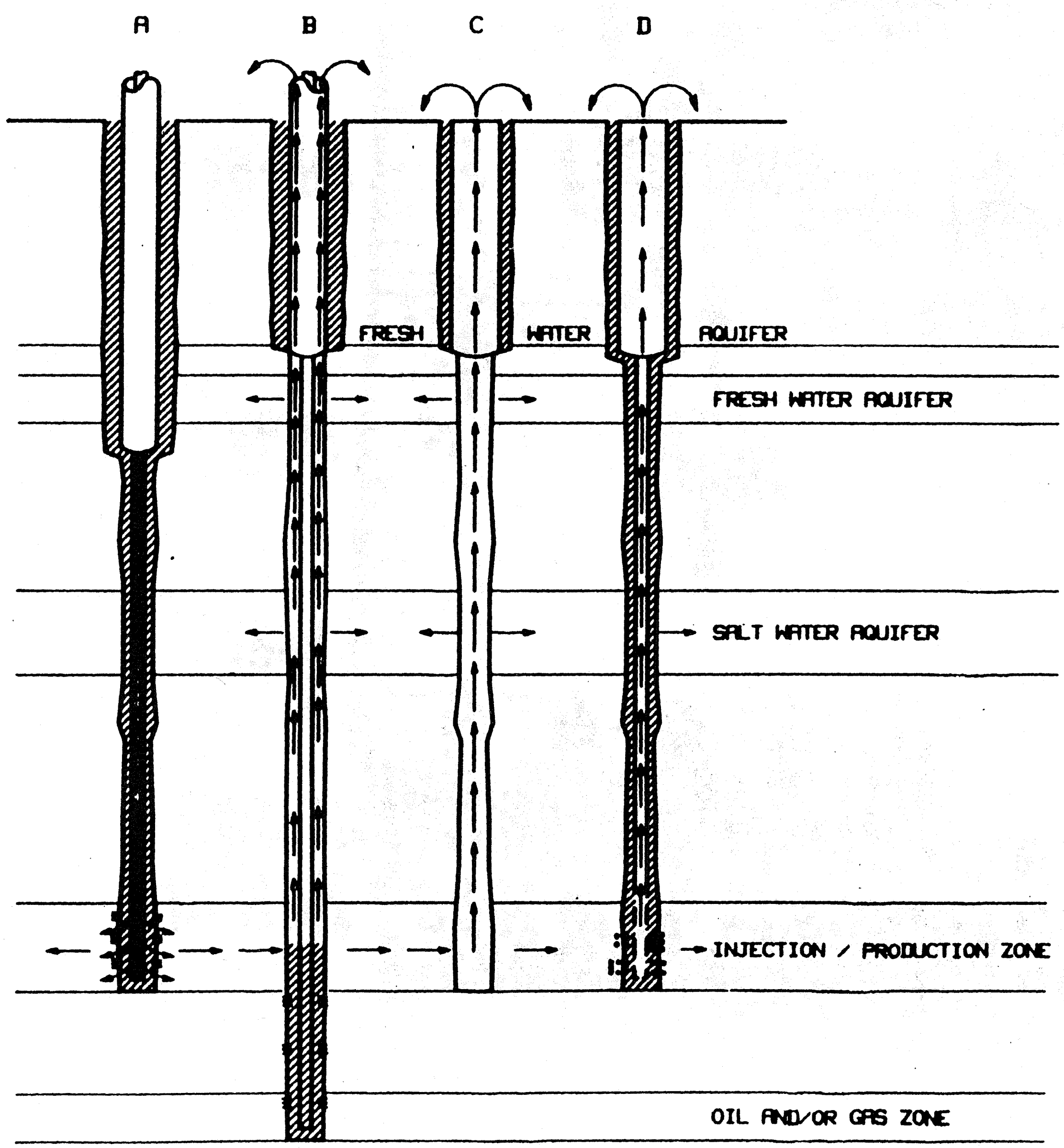

PROTOCOL FOR IDENTIFYING
ABANDONED WELLS IN AN AREA OF REVIEW
SEARCH DATA SOURCES
STATE/ FEDERAL RECORDS
INTERNAL DOCUMENTS
COMM. LOG. CO.'S
OIL COMPANY RECORDS
IDENTIFY WELLS IN AREA OF REVIEW
PENETRATE CONFINING / INJECTION ZONE
N
Y
OK
FORMATION TYPE UNCONSOLIDATED/INDURATED
DRILLING METHOD ROTARY/CABLE
PLUGGING RECORDS AVAILABLE
N
Y
INTERVIEW
SEARCH CEMENT, INJECTION AND/OR PRODUCTION RECORDS
PLUGGED PROPERLY
N
Y
OK
OPERATORS
LEASE OWNERS
CONS. GEOLOGIST
PLUG RECORDS FOUND
N
N
Y
SEARCH CEMENT, INJECTION AND/OR PRODUCTION RECORDS
PLUGGED PROPERLY
Y
OK
MODEL
POTENTIAL UPWARD MIGRATION
NO UPWARD MIGRATION
OK
LOCATE ABANDONED WELL
MAGNETOMETER
MAP COORDINATES
WELL LOG COORDINATES
METAL DETECTOR
SURVEYOR
OTHER
WELL LOCATED
Y
N
N
N
REPLUG
OTHER
LOWER INJECTION ZONE
LOWER INJECTION RATE
OK

Figure 1

POTENTIAL PATHS OF FLUID MIGRATION FROM CLASS II INJECTION WELLS



EXPLANATION

A - CLASS II INJECTION WELL

B - PRODUCTION WELL - COMPLETED IN DEEPER ZONE, ANNULUS PARTIALLY UNCEMENTED TO SURFACE, FORMATION PRESSURE >> STATIC ANNULAR MUD COLUMN

C - IMPROPERLY PLUGGED AND ABANDONED DRY HOLE - PENETRATING THE INJECTION / PRODUCTION ZONE FORMATION PRESSURE >> STATIC FLUID COLUMN

D - IMPROPERLY ABANDONED PRODUCTION WELL - DEPLETED WELL WITH PRODUCTION STRING LEFT OPEN TO INJECTION ZONE, NO CEMENT OR MUD PLUGS

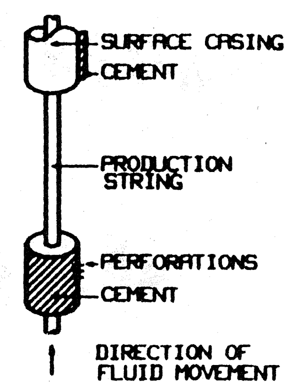


Figure 2

Stepwise Dehydration of Clay in Gulf Coast Well, Chambers County, Texas

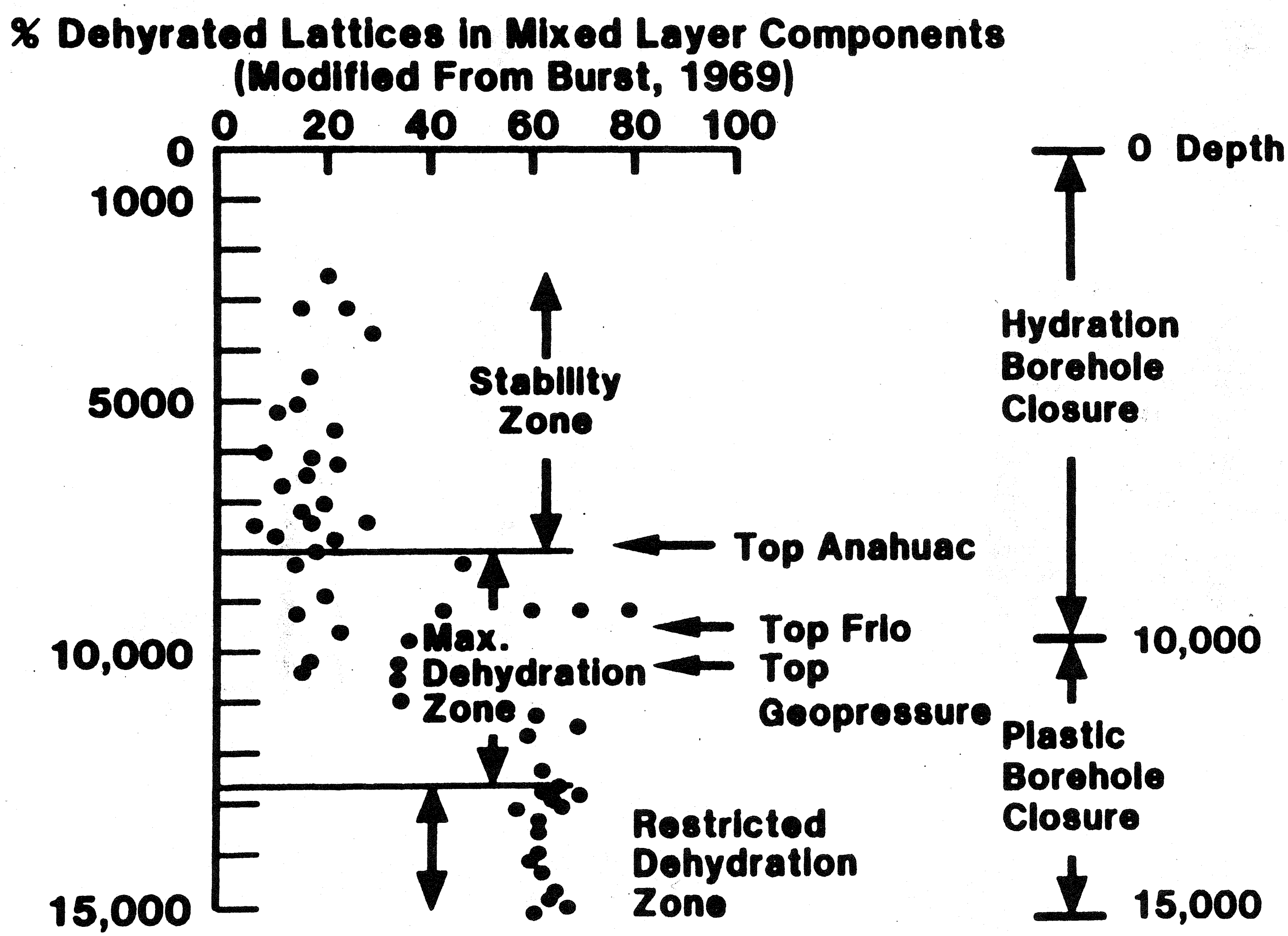


Figure 3

CONSOLIDATED AND UNCONSOLIDATED

ROCK TYPES IN TEXAS

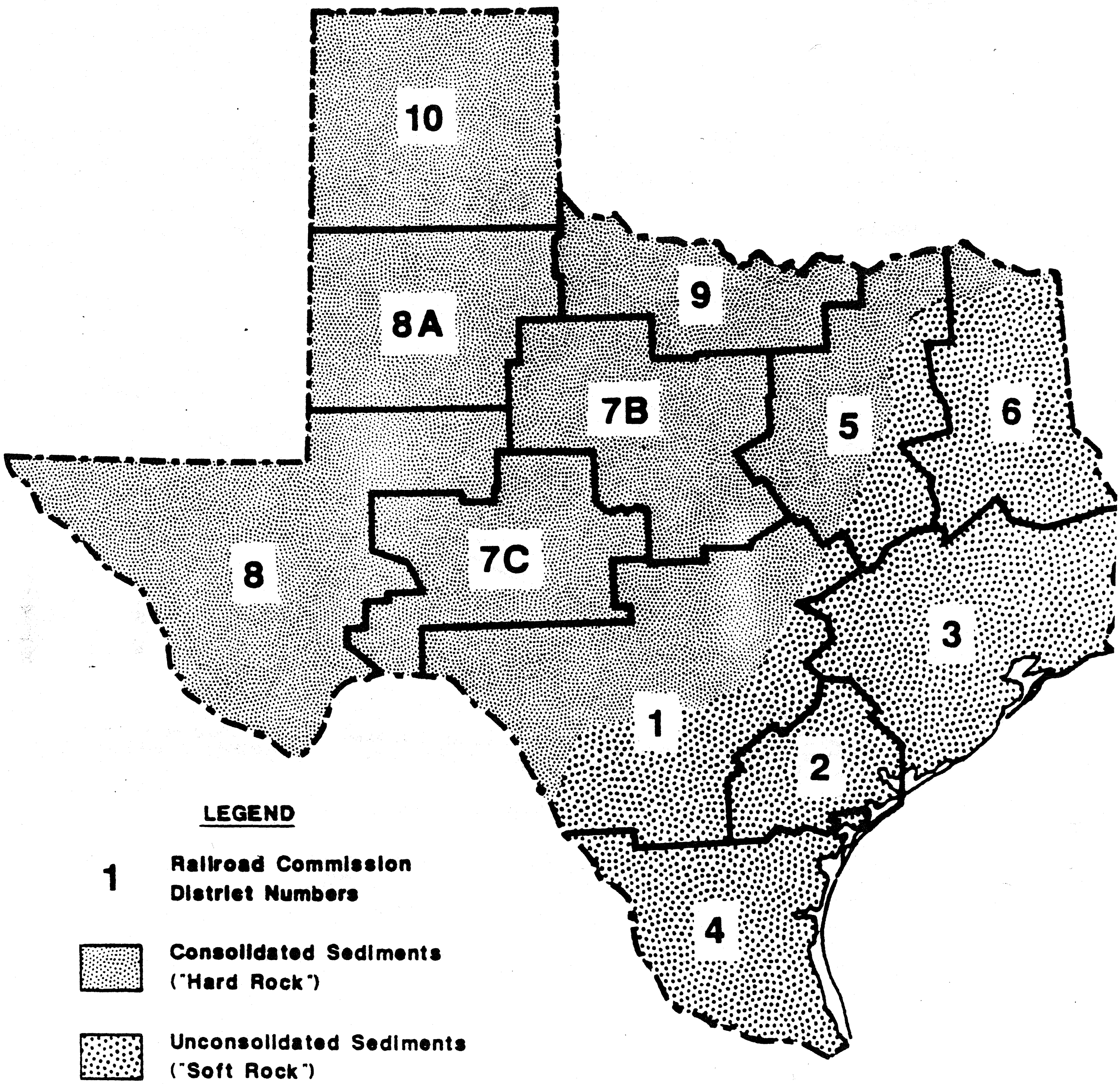


Figure 4

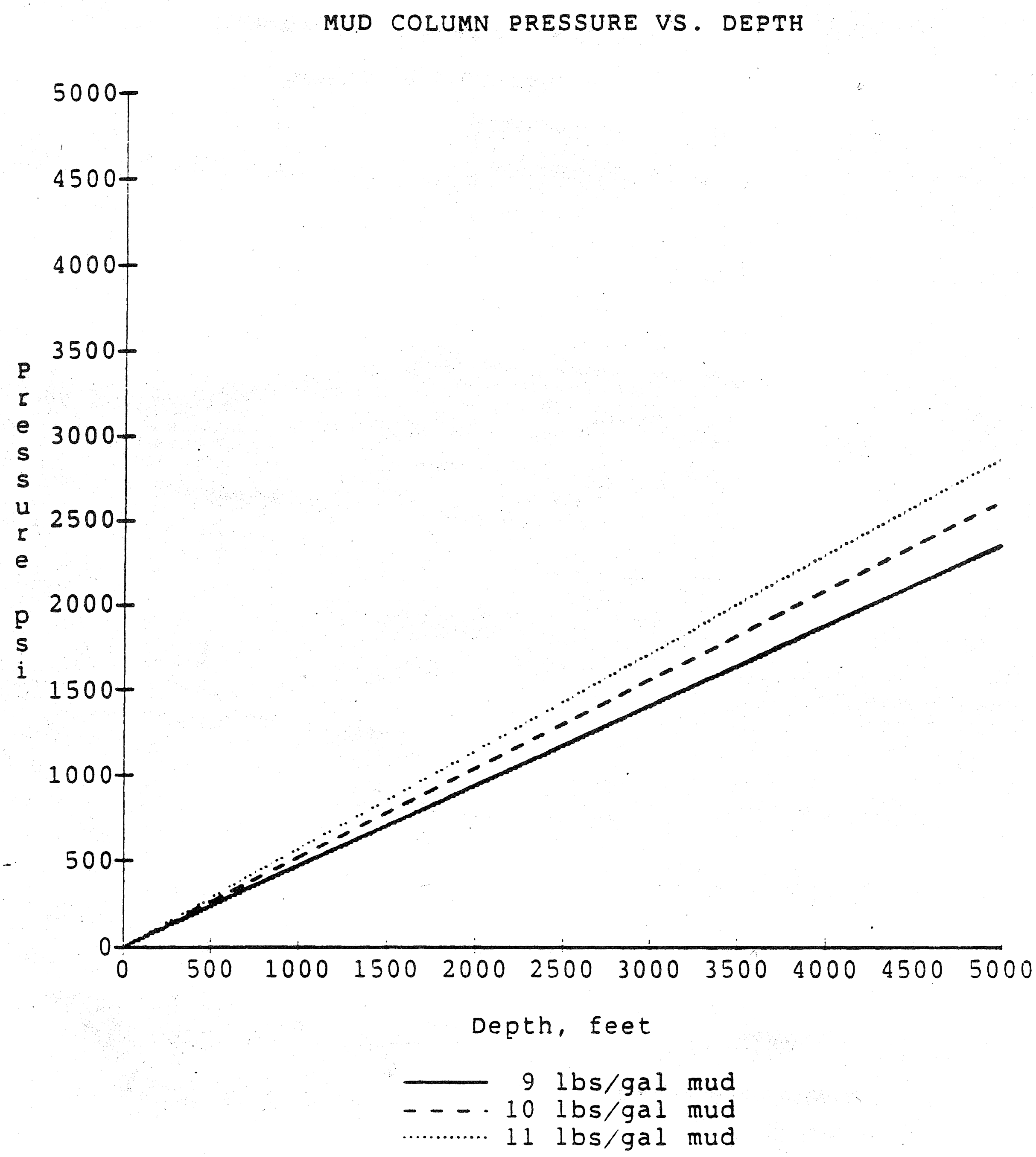

MUD COLUMN PRESSURE VS. DEPTH
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Pressure psi
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Depth, feet
9 lbs/gal mud
10 lbs/gal mud
11 lbs/gal mud

Figure 5

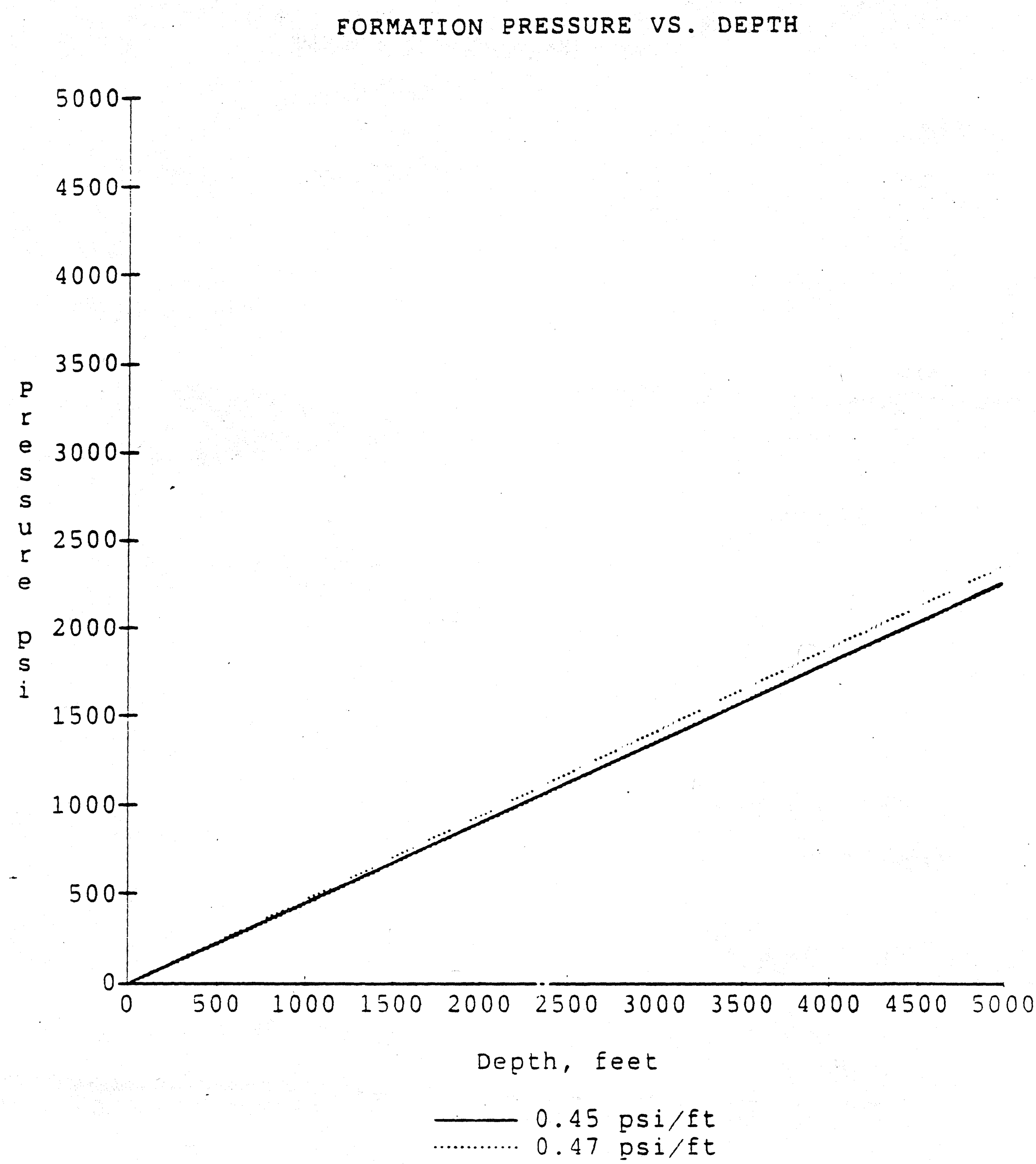
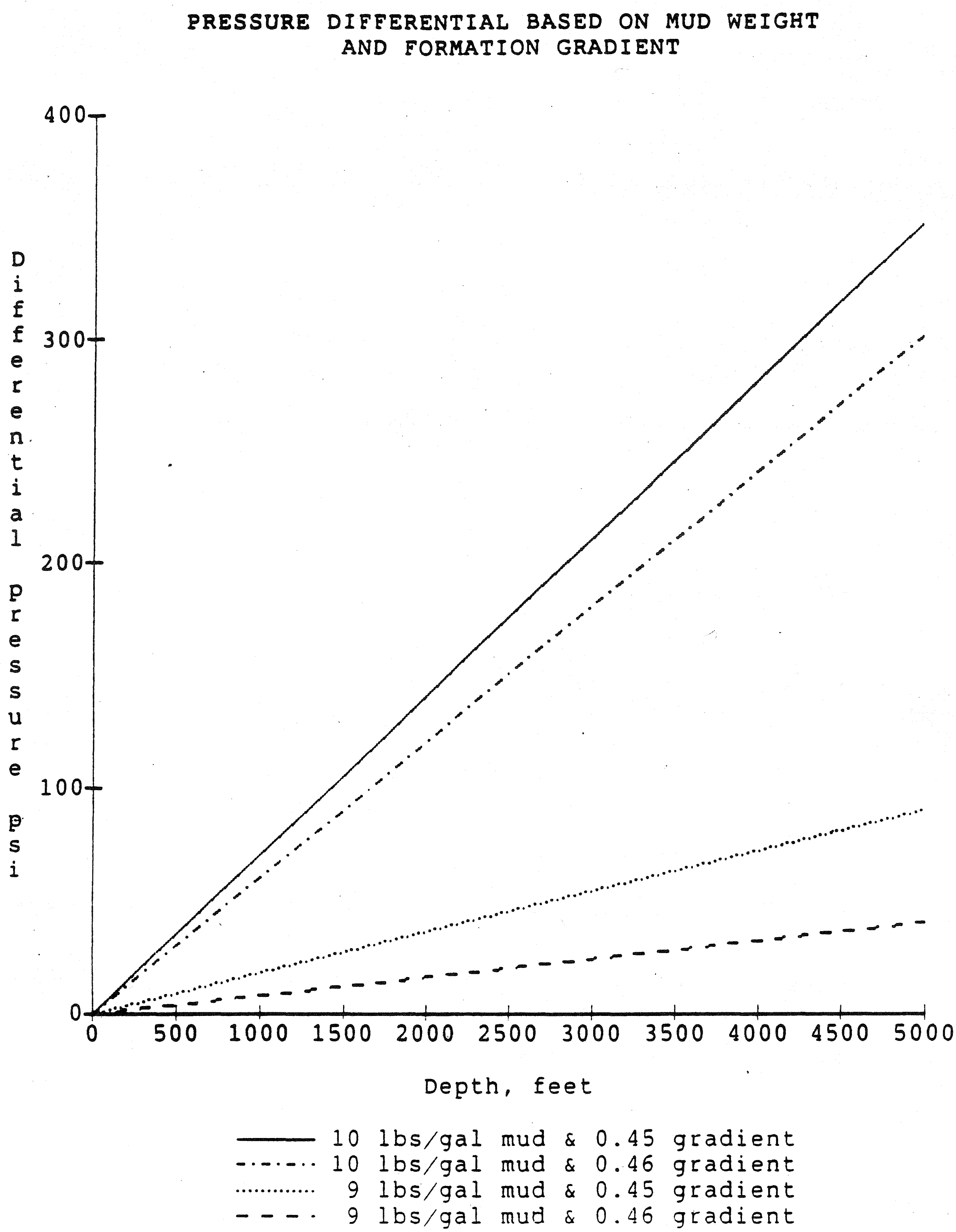

FORMATION PRESSURE VS. DEPTH
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Pressure psi
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Depth, feet
0.45 psi/ft
0.47 psi/ft

Figure 6



PRESSURE DIFFERENTIAL BASED ON MUD WEIGHT
AND FORMATION GRADIENT
Differential pressure psi
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Depth, feet
10 lbs/gal mud & 0.45 gradient
10 lbs/gal mud & 0.46 gradient
9 lbs/gal mud & 0.45 gradient
9 lbs/gal mud & 0.46 gradient

Figure 7

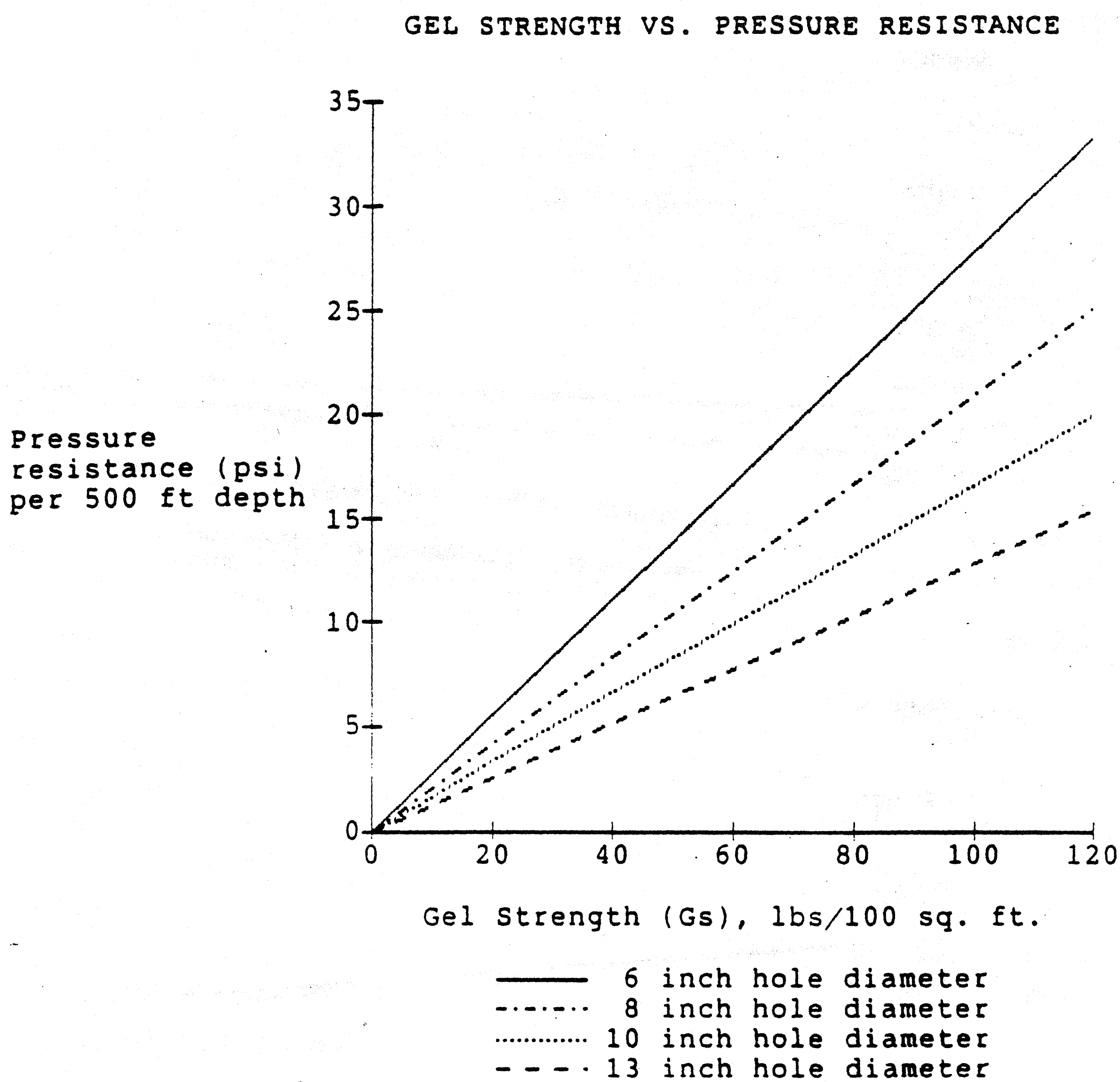
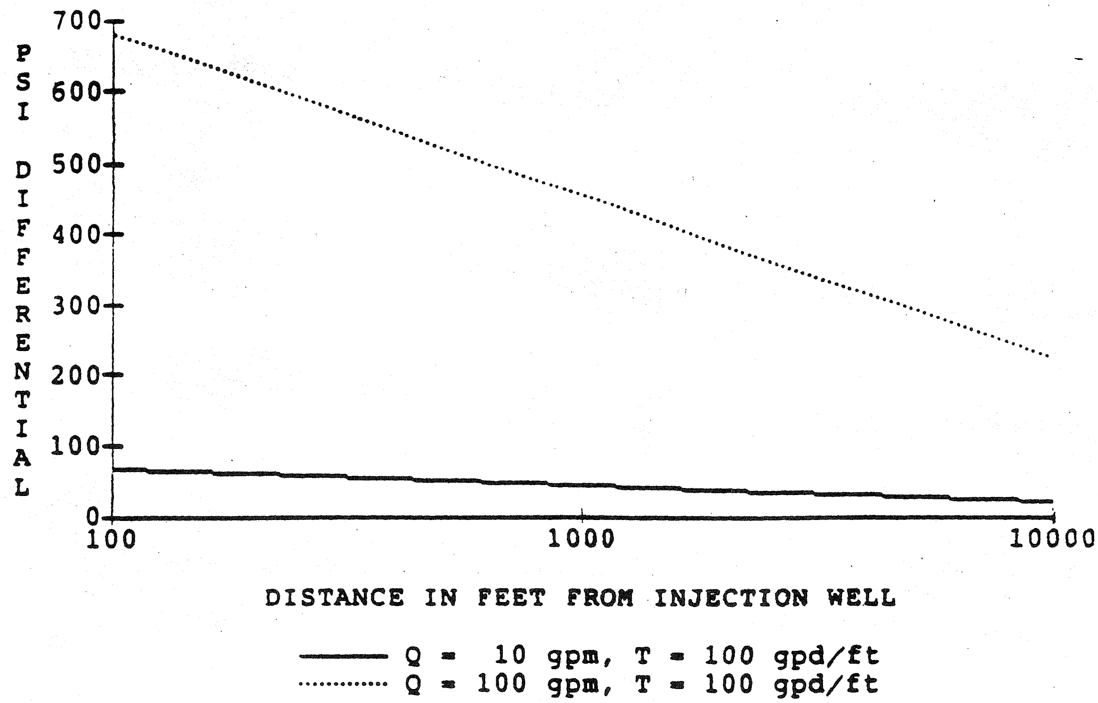
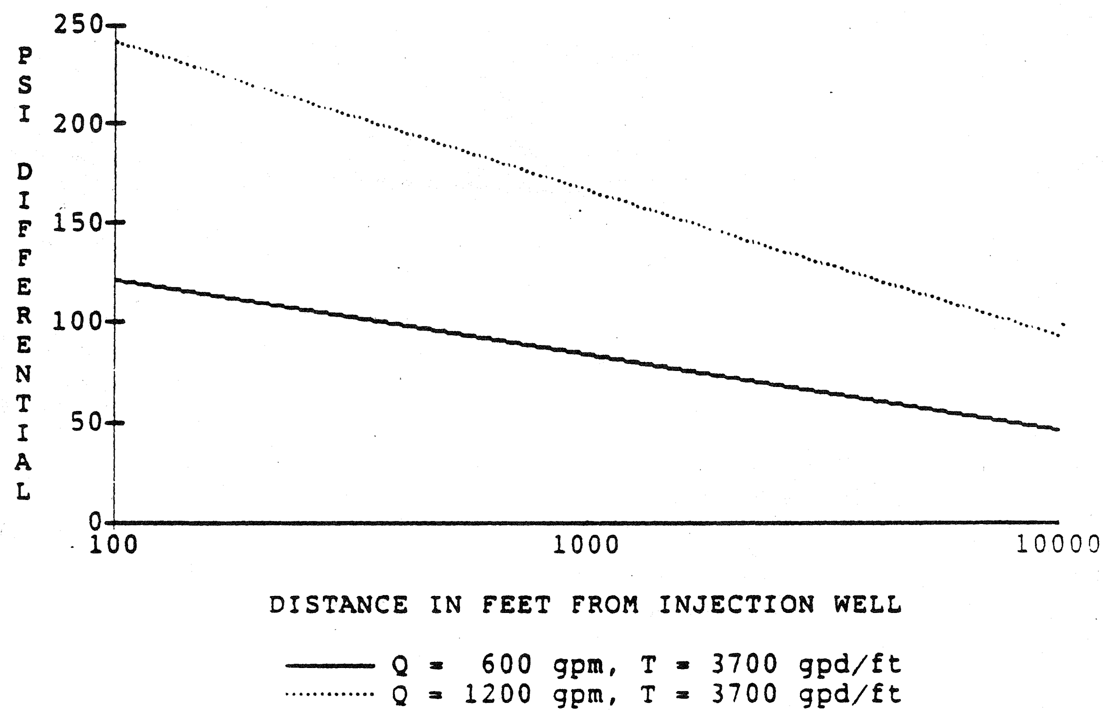

GEL STRENGTH VS. PRESSURE RESISTANCE
Pressure resistance (psi) per 500 ft depth
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Gel Strength (Gs), lbs/100 sq. ft.
6 inch hole diameter
8 inch hole diameter
10 inch hole diameter
13 inch hole diameter

Figure 8

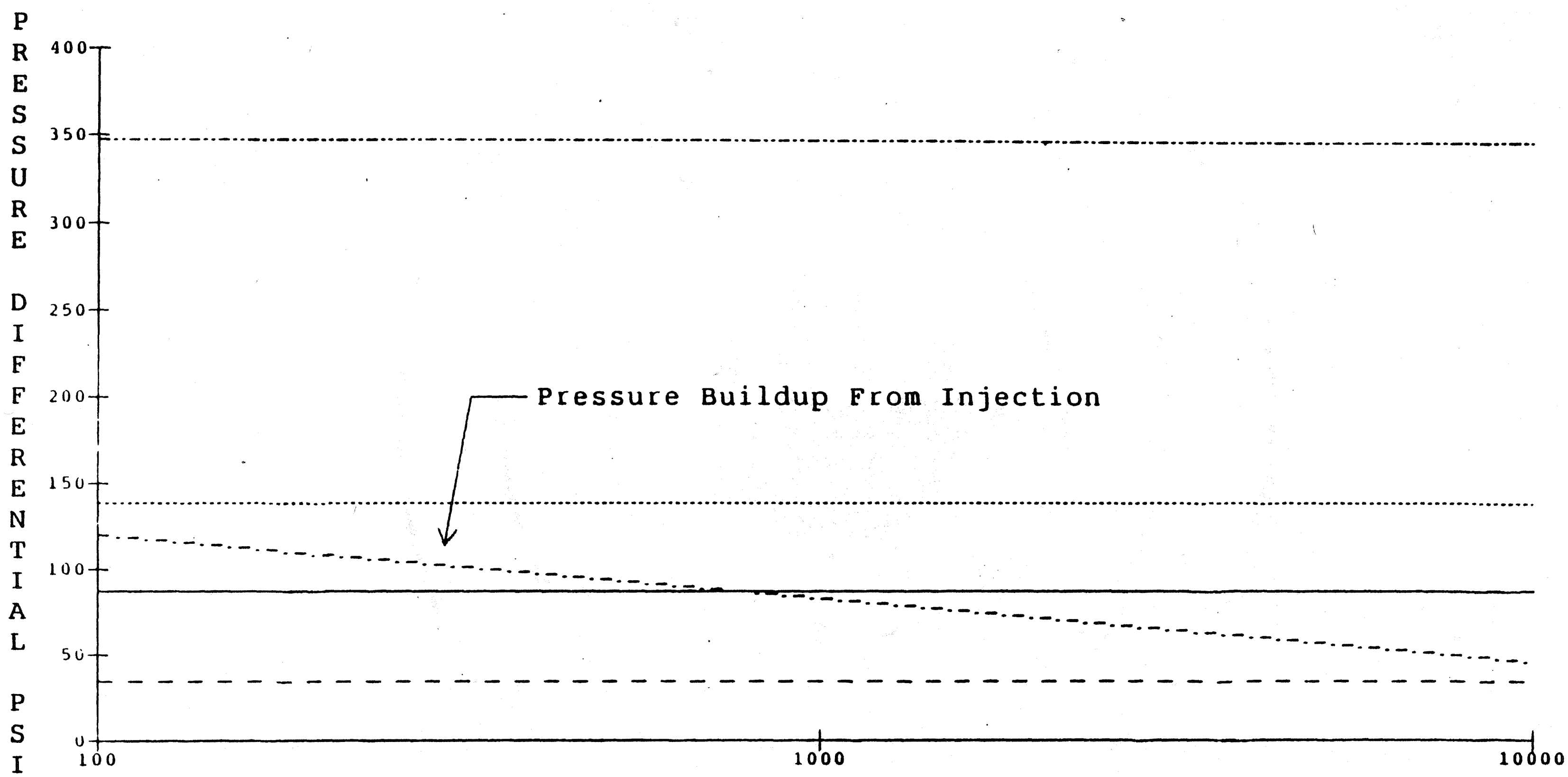




Injection Zone Pressure Buildup After 30 Years vs. Distance and Relationship Between Transmissivity and Injection Rates.

Figure 9

AREA OF REVIEW CALCULATION



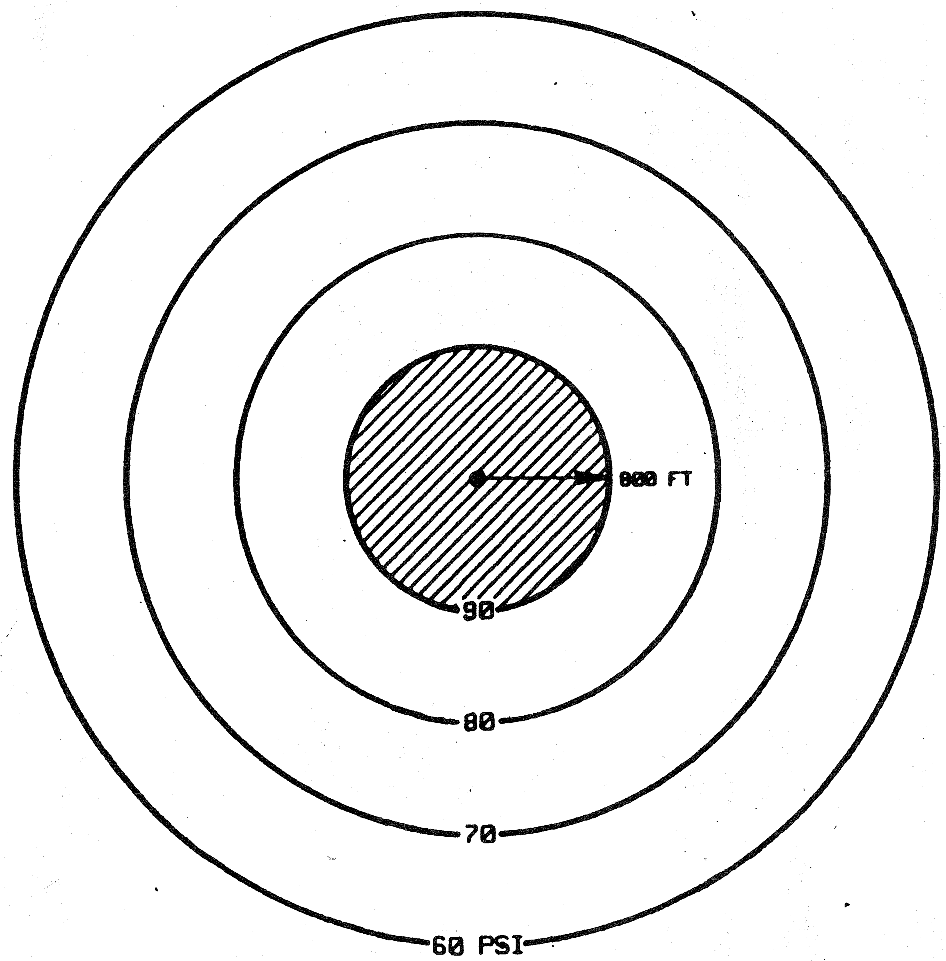
DISTANCE IN FEET FROM INJECTION WELL

-·-·-·- Mud pressure resistance, 10 lbs/gal mud @ 5000 ft
······· Mud pressure resistance, 10 lbs/gal mud @ 2000 ft
——— Mud pressure resistance, 9 lbs/gal mud @ 2000 ft
– – – Mud pressure resistance, 9 lbs/gal mud @ 2000 ft

Area of Review Calculation Based on Formation Gradient = 0.45 psi/ft, 9 lbs/gal Mud at 5000 ft Depth, and an Injection Zone where Q = 600 gpm and T = 3700 gpd/ft. Other Weight Muds at Various Depths Shown.

Figure 10

CALCULATED PRESSURE INCREASE DISTRIBUTION
AREA OF REVIEW CALCULATION



PARAMETERS

Q = 600 gpm
T = 3700 gpd/ft
(30 yr. injection)
9 lbs/gal MUD @ 5000 FT

EXPLANATION

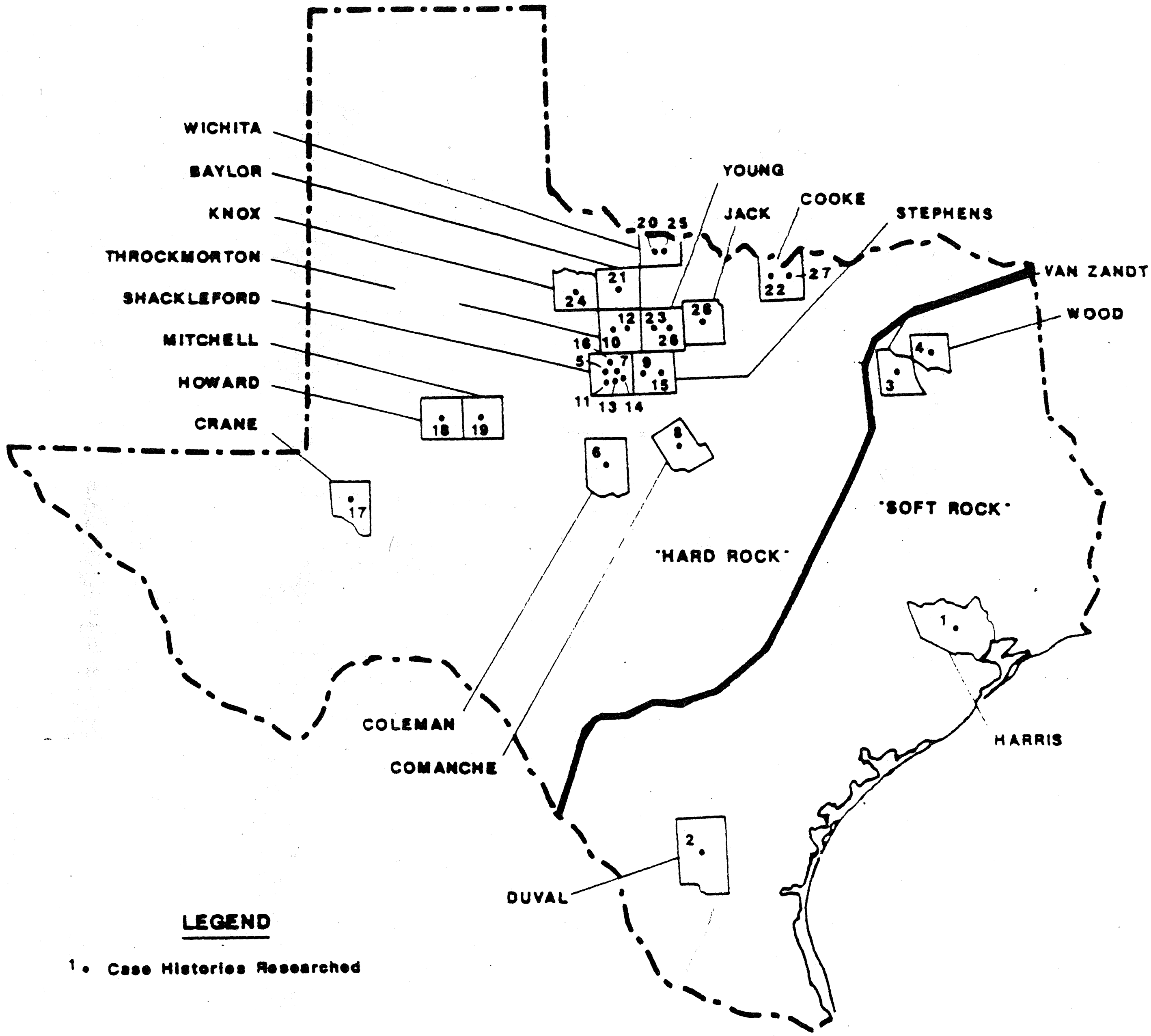
CALCULATED AREA OF REVIEW

Figure 11

Case 1

CASE HISTORIES RESEARCHED

FROM TEXAS RAILROAD COMMISSION FILES

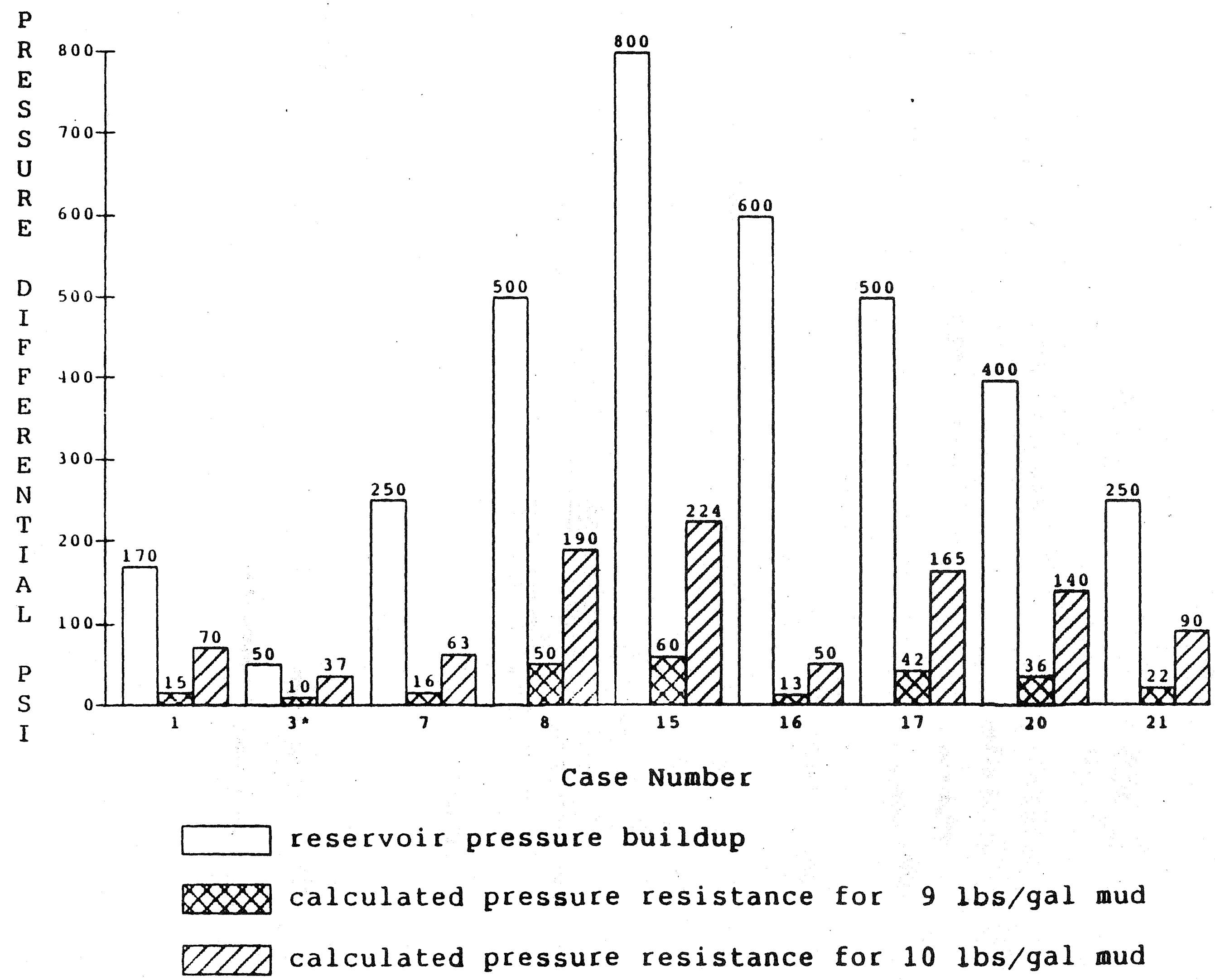


LEGEND

1 • Case Histories Researched

Figure 12

CASE 1
RESERVOIR PRESSURE BUILDUP VS. MUD PRESSURE RESISTANCE



* limited reservoir data available

ure 13

CASE 1
TOTAL DEPTH OF LEAKING WELLS VS. NUMBER OF OCCURRENCES

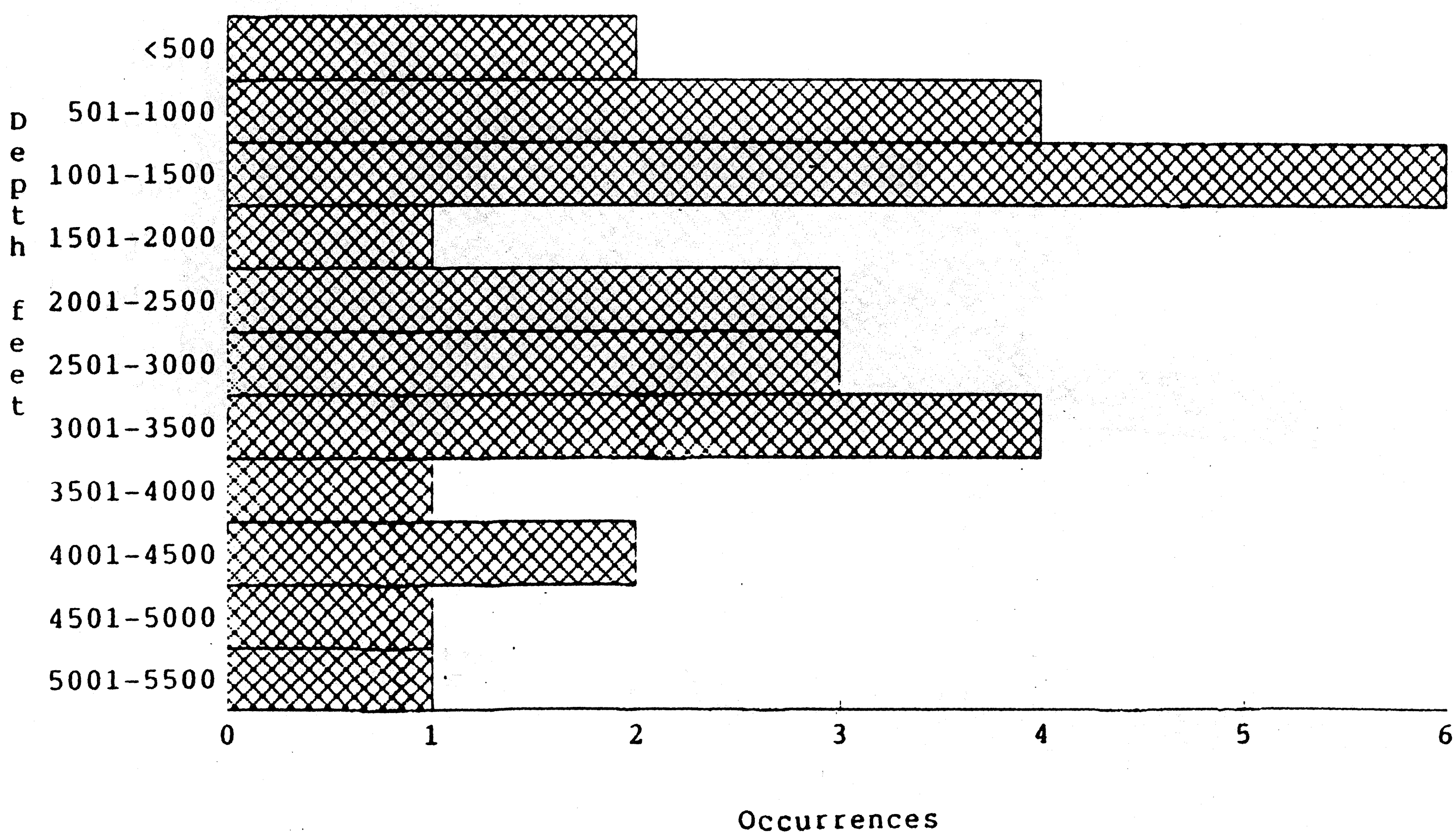


Figure 14

CASE 1
DISTANCE FROM LEAKING WELLS TO SUSPECT CLASS II WELLS

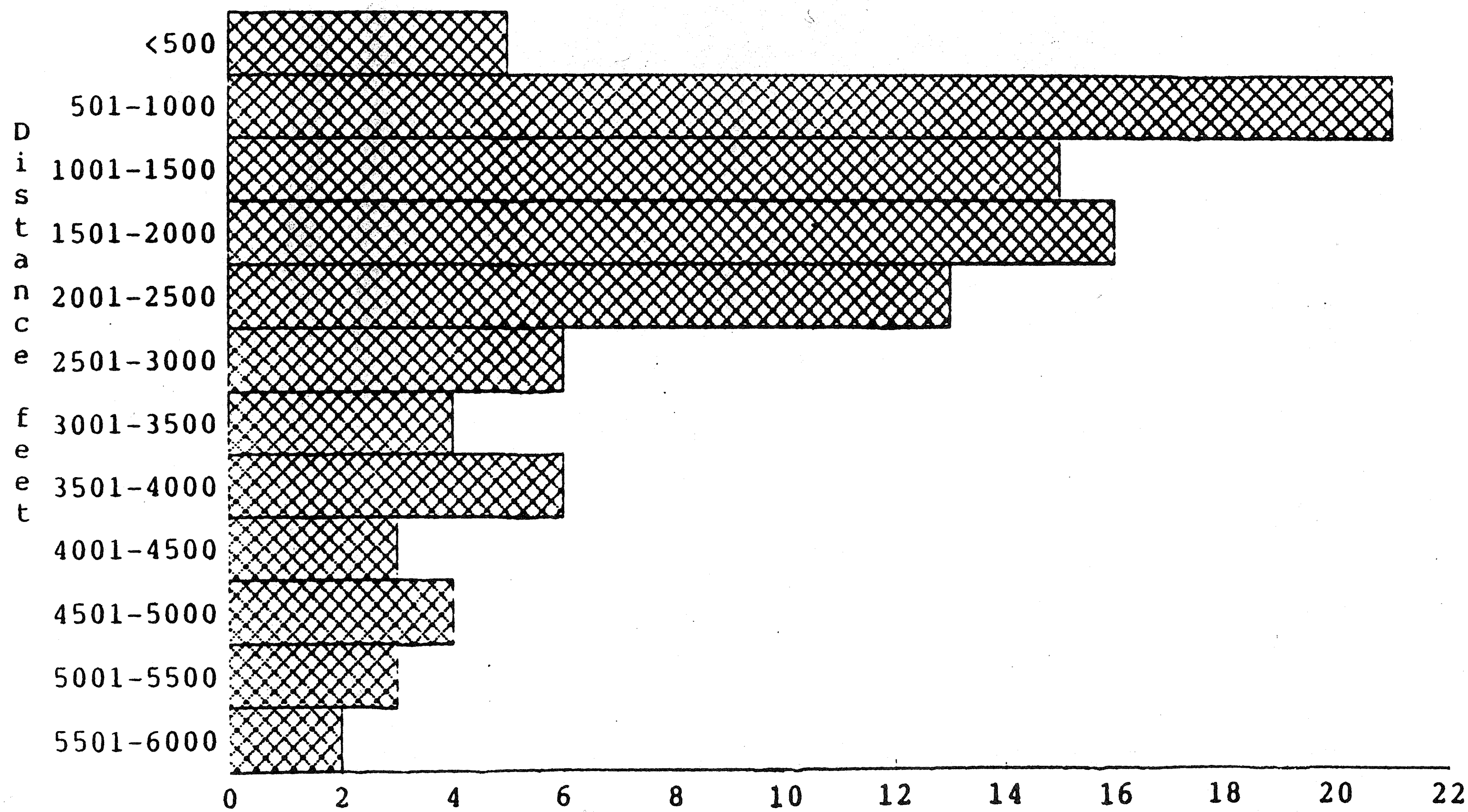


Figure 15

Case 2

PROPER PLUGGING HEARING SURVEY

SELECTED GULF COAST COUNTIES

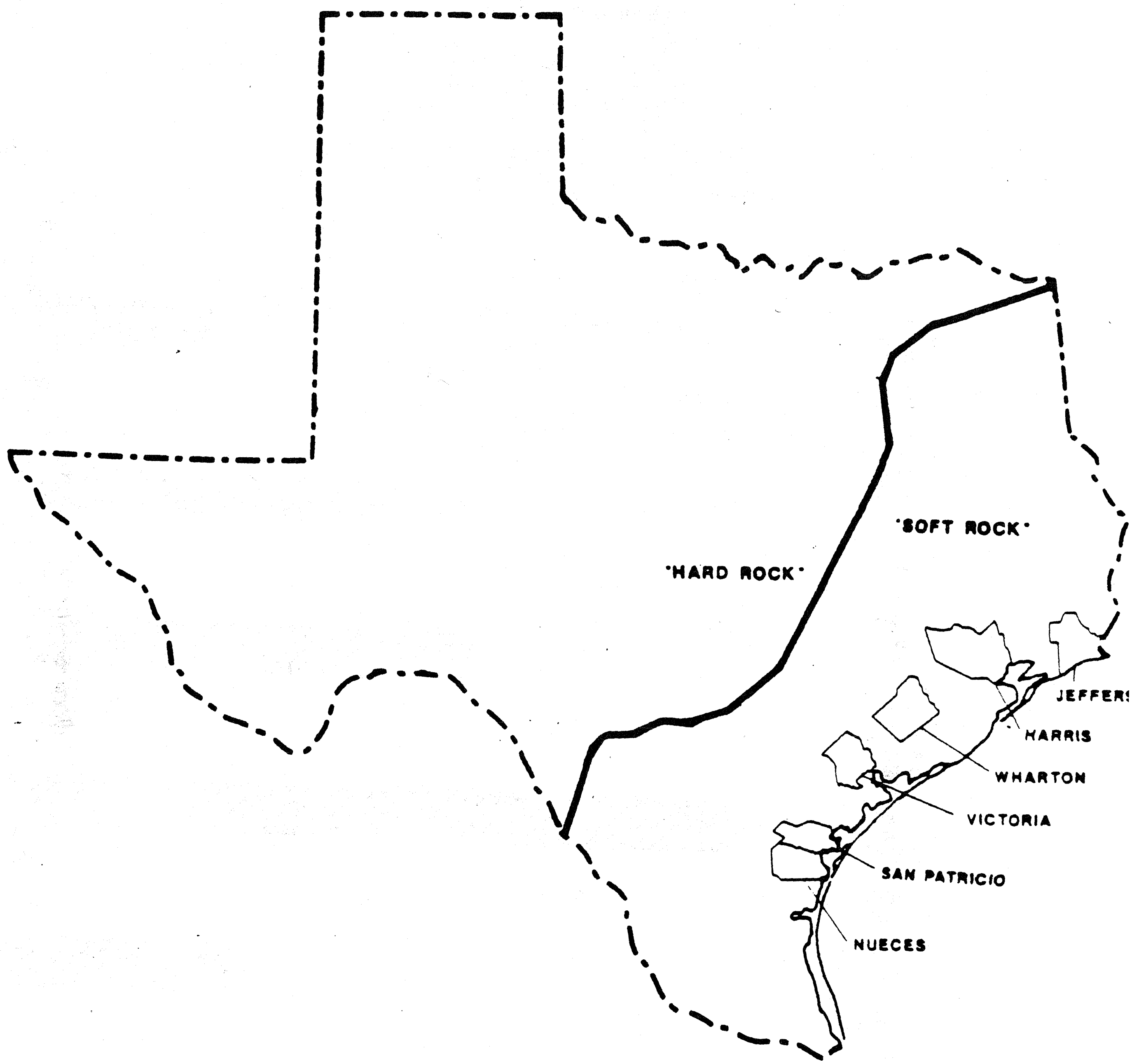


Figure 16

CASE 2
NUMBER OF FIELDS EXAMINED, PROPER PLUG HEARINGS, AND
POLLUTION INCIDENTS REPORTEDLY CAUSED BY CLASS II INJECTION

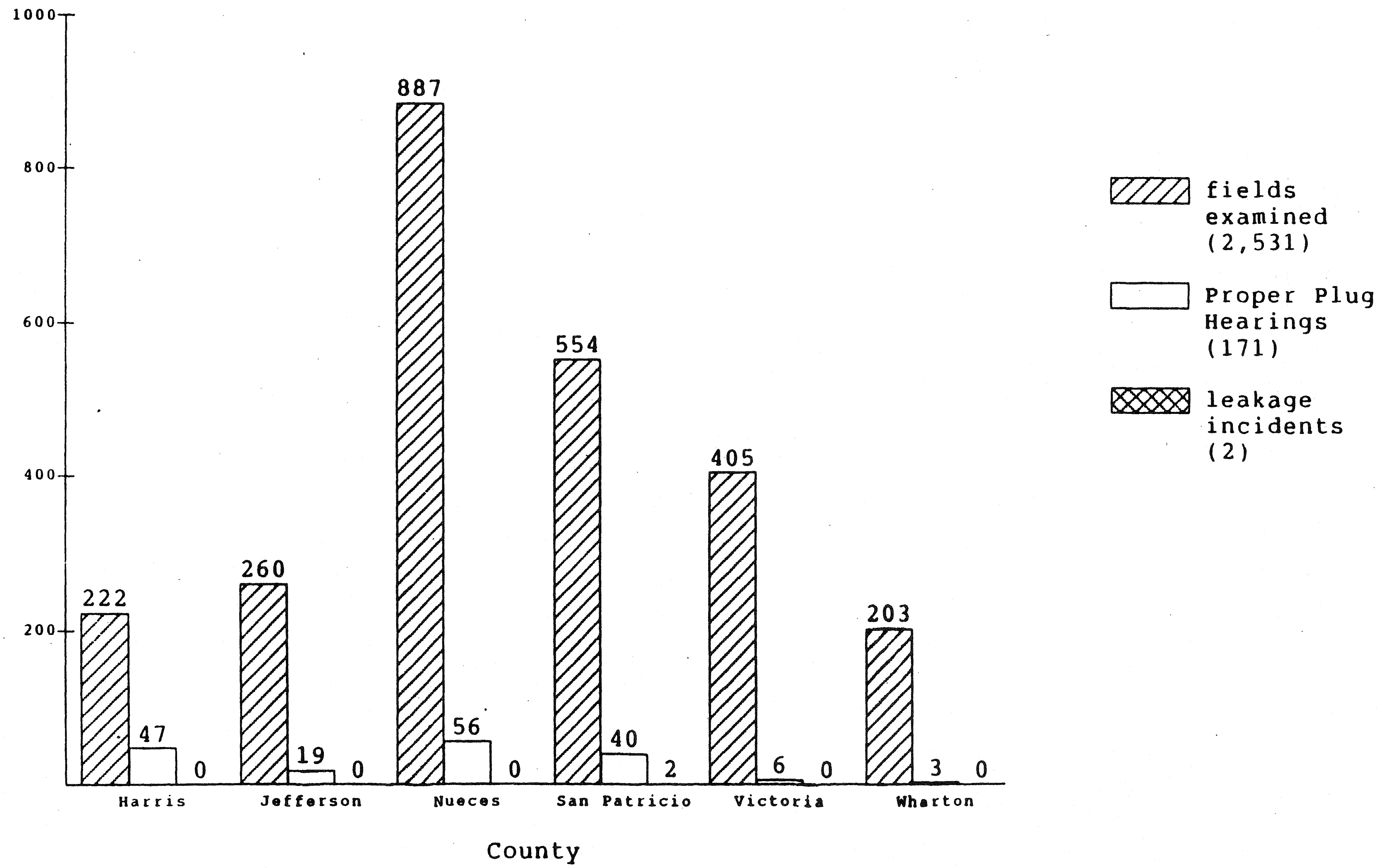


Figure 17

Case 3

PROPER PLUGGING HEARING SURVEY

SELECTED RAILROAD COMMISSION DISTRICTS

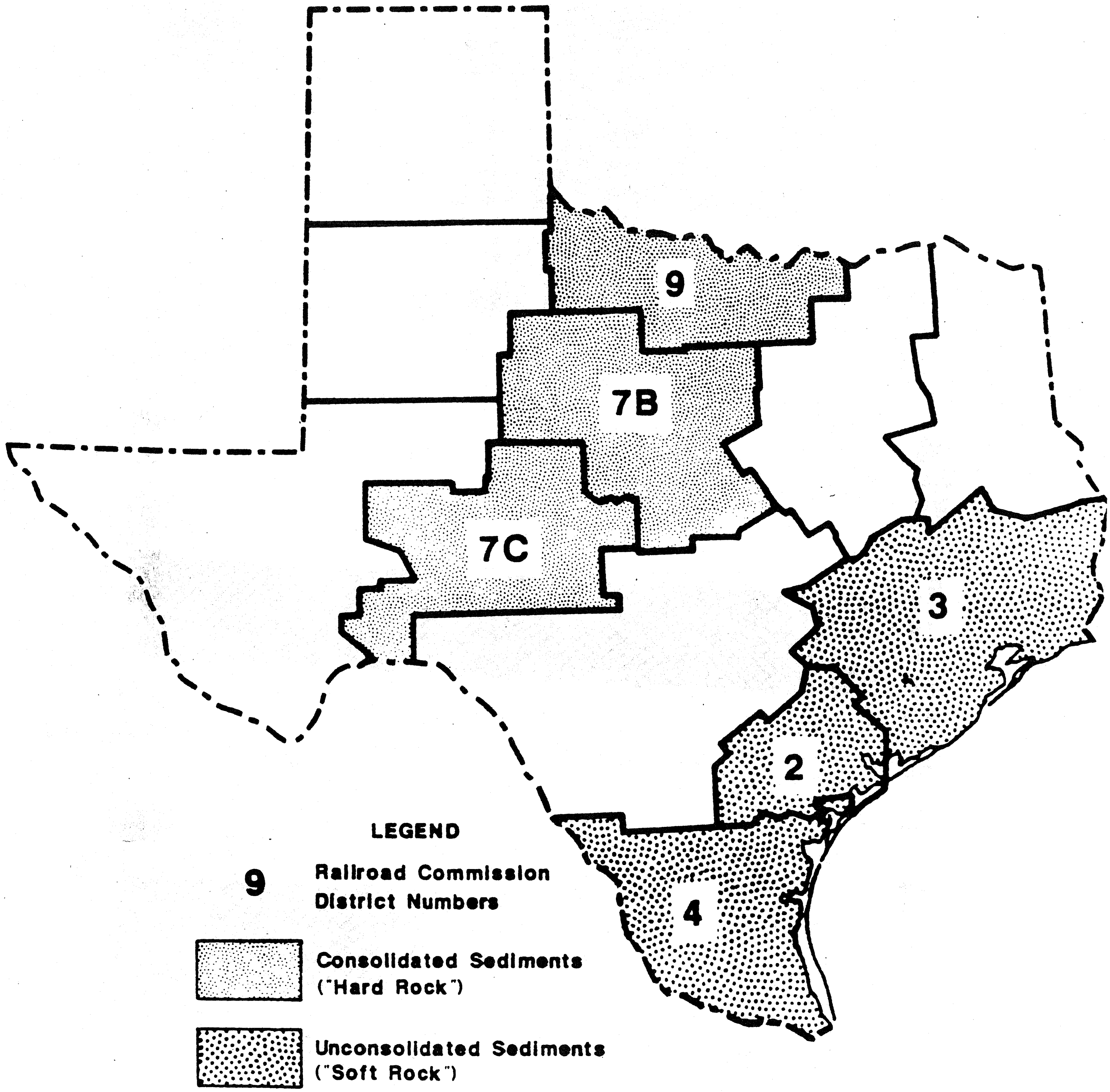


Figure 18

CASE 3
CONSOLIDATED VS. UNCONSOLIDATED FORMATIONS

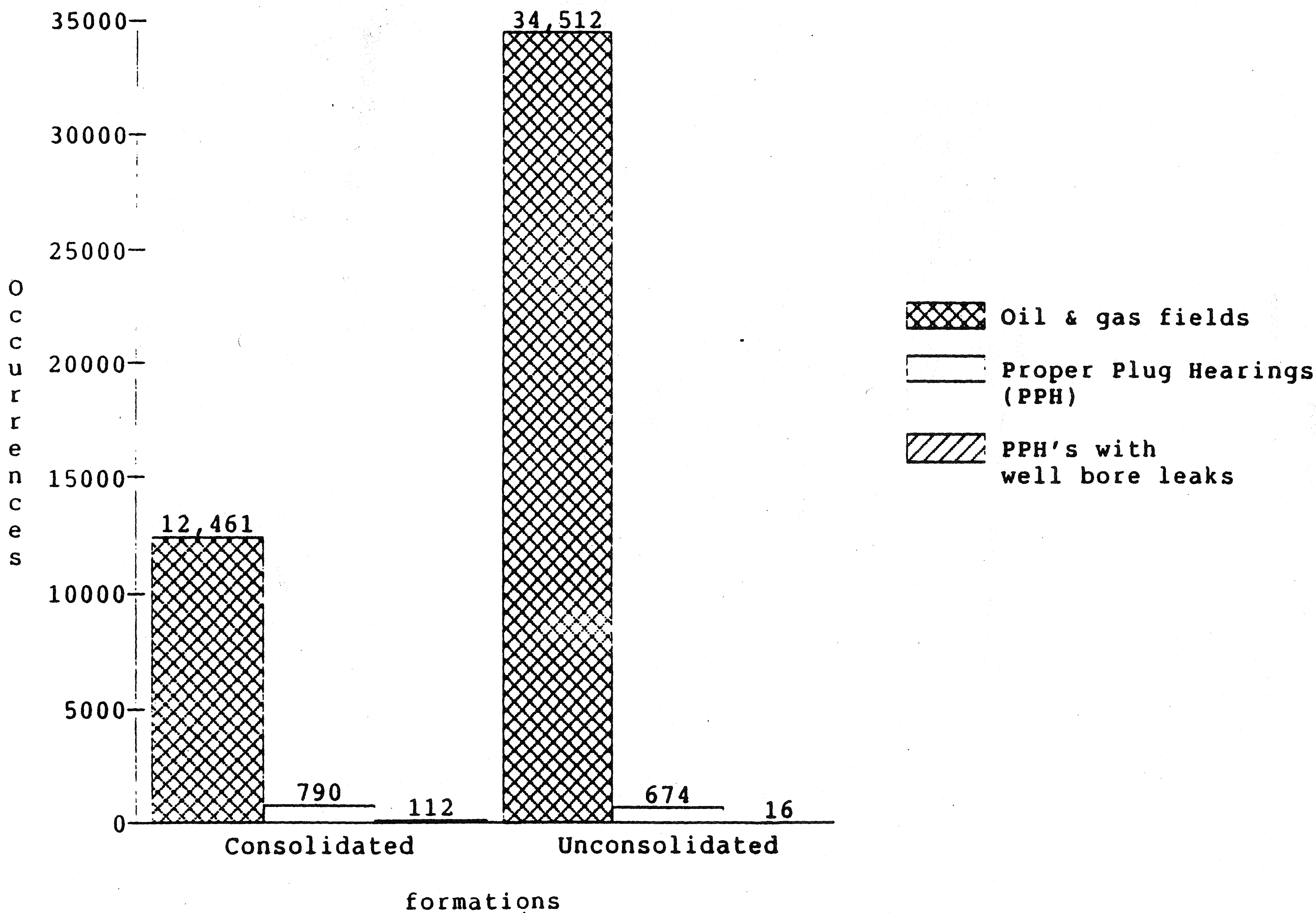


Figure 19

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Biographical Sketches

James E. Clark holds a B.S. in geology (1972) from Auburn University an M.S. in geophysical sciences (1977) from Georgia Institute of Technolo As a geohydrologist with Law Engineering Testing Co., he worked on suitabili studies of salt domes as repositories for nuclear waste. He is a consultant with Du Pont's (E. I. du Pont de Nemours & Co., Inc., Engineering Department, P. O. Box 3269, Beaumont, TX 77704) solid waste and geological engineering group and is active in permitting and evaluation of disposal wells.

Milton R. Howard received his B.S. degree in geology from Texas A&M University (1985). He served as a petroleum geologist for SOHIO and Albaine, active in on-shore database evaluation and oil and gas exploration. In 1985 he joined the waste and geological engineering group of Du Pont as a contract consulting environmental geologist responsible for permitting and evaluation of the Federal UIC Class I disposal wells.

Diane K. Sparks received her B.S. degree (1977) in geology and her M.S. degree (1978) in geology from Bowling Green State University. She was a petroleum geologist with Amoco Production Company and Helmerich and Payne, Inc. Sparks is now a consulting geologist and currently works as a contract geologist for the Engineering Service Division of Du Pont, in evaluation of Class I disposal wells and fluid migration studies.

APPENDIX 4-15

Appendix 4-15

Test Results for the Nora Schultz Well No. 2 (Pearce, 1989)

KEN E. DAVIS
ASSOCIATES

January 6, 1989

Mr. James E. Clark
E. I. DuPont de Nemours & Company
ESD
P. O. Box 3269
Beaumont, Texas 77704

Re: Test Results for the Nora Schulze Well No. 2
KEDA Job No. 10-1182

Dear Mr. Clark:

This letter report summarizes the test results that KEDA, Inc. (KEDA) has collected for mud samples obtained from the upper 730+ feet of the Nora Schulze Well No. 2 located in Nueces County, Texas (Figure 1).

The Nora Schulze No. 2 well was drilled and completed between November 13, 1959 and November 25, 1959. On November 25, 1959 this well was plugged and abandoned. According to Dresser-Magcobar records, Attachment 1, the well was drilled to total depth with a mud weight that ranged between 10.6 and 11 ppg for depths below 7300 feet. This mud was used to fill uncemented portions of the cased hole during the final plugging operations.

On August 26, 1988, KEDA commenced operations to reenter this well for the purposes of cementing the top portion of the well from 1035 feet to the surface.

However, before initiating the plugging operations requested by the Texas Water Commission (TWC), KEDA, in consultation with the TWC, elected to core the mud in the hole using a special coring bit and tubing string which could be pushed into the mud.

The tubing, which initially contacted the mud 12 feet below the surface, was pushed into the cased hole to a total depth of 734 feet. At this depth, the shear strength of the mud exceeded the weight that could be applied on the tubing, and no further progress could be made. Therefore, the tubing was pulled out of the hole and the recovered mud was allowed to flow into 5 gallon buckets. The bottom 18 feet of sample did not flow from the tubing and was, therefore, retained in the three 6-foot pipe joints that were initially installed on the tubing for this purpose.

3121 SAN JACINTO HOUSTON, TX 77004
SUITE 102 (713) 522-5784

. BOX 80558 BATON ROUGE, LA 70898
805 SUN BELT COURT BATON ROUGE, LA 70809
(504) 293-2561

300 N. MICHIGAN SOUTH BEND, IN 46601
SUITE 409 (219) 287-2282

WELL SYSTEMS FOR INDUS

A total of 22 mud samples were obtained from the well. Each 5 gallon bucket contains the mud that was captured in each 33-foot tubing joint below 111 feet. The depths reported for each mud represents the midpoint for the sample that was collected from each tube. The first two samples represent the mud from two joints of tubing.

Table I presents the data that was collected on the mud samples which were recovered from the Nora Schulze No. 2 well. The average mud weight in the column was determined to be 11.1 lbs/gal and the average shear strength for Samples 3 through 17 was 260 lbs/100 ft^2. The average gel strength was 267 lbs/100 ft^2.

If you have any questions, or require more details, please contact me at your earliest convenience.

Sincerely,

KEN E. DAVIS ASSOCIATES

Mark S. Pearce

Mark S. Pearce
Regional Manager

MSP/js
Attachments

WELL : NORA SCHULZE No. 2

LOCATION : CORPUS CHRISTI AREA

MUD TYPE : LIGNOSULFATE ?

MUD DENSITY : 11.0 POUNDS/GALLON

GEL STRENGTH : 0/3 POUNDS FORCE/100 FEET^2

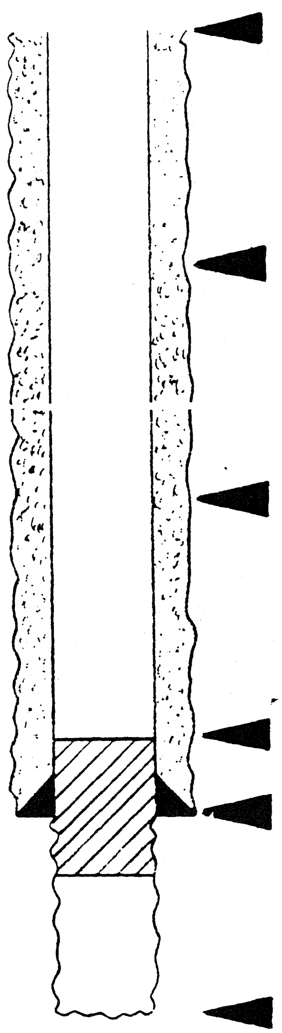
DRILLING COMMENCED : NOVEMBER 13, 1959

WELL P&A : NOVEMBER 25, 1959

DATE OF MUD SAMPLE : AUGUST 26, 1988

DEPTH OF MUD SAMPLES : 12' TO 754' BGL

WELL DIAGRAM



KEN E. DAVIS ASSOCIATES

HOUSTON, TX BATON ROUGE, LA SOUTH BEND, IN

NORA SCHULZE No. 2
FISHER AND DAVIDSON
ROBSTOWN, TEXAS

DATE	CHECKED BY	JOB NO
DRAWN BY	APPROVED BY	DWG NO

ATTACHMENT 1

WELL DATA SHEET

Magcobar DRESSER

MAG-380 A

OPERATOR: FISHER & DAVIDSON	SURVEY SEC. Blk 22 T A-572 R	CASING SIZE	DEPTH
WELL: Schultz #2	FIELD: E. Minnie	SURFACE	
CONTRACTOR: Gilmour Drilling Company	COUNTY: Nueces	INTERMEDIATE	
ENGINEER: Kenneth Stewart	STATE: Texas	PRODUCTION	

DATE	DEPTH	WT.	VIS.	AV	PV	YP	GELS		pH	W/L	PF	Cl PPM.	CA PPM.	SOL %	OIL %	H.T.H.P.
	4500	9.6	36				0	5		14.4		1300				
	6500	10.0	47				0	3		8.6		1800			10	
	7000	10.2	62				5	15		5.6		2200			12½	
	7300	10.6	47				0	3		5.6		2000			12	
	7500	10.7	45				0	3		5.2		2100			12	
	7600	10.6	48				0	5		5.6		2100			11½	
	7900	10.6	50				0	5		5.2		2100			10	
	8470	11.0	47				0	3		5.0		2100			9	

TOTAL MUD COST: $2,987.00

TOT

REMARKS

Drills real good to 6500 f
Below this depth drills ve
Oil usually added at 6500

The 10.2 pound per gallon
go to 7500 feet.
Had a 10.8 pound per gallon
7600 feet.
Had a 11.0+ pound per gall
8000 to 8500 feet.

Very bentonetic. Takes lot
water.

Natural weight is about 10.
pounds per gallon.

DATE SPUD: DATE T.D.: B.H.T. COMPLETION FLUID TYPE: COST:

PACKER MUD TYPE: COST:

TABLE I

RECOVERED MUD PROPERTIES FOR NORA SCHULZE NO. 2 WELL

SAMPLE NO.	DEPTH (ft)	MUD WEIGHT (lb/gal)	SHEAR STRENGTH (lbs/100 ft^2	GEL STRENGTH (lbs/100 ft^2
1	---	---	---	---
2	60	12.0	540	304
3	111	10.9	230	296
4	174	11.0	310	295
5	207	11.2	190	<320
6	240	10.9	170	284
7	273	10.7	180	237
8	306	10.9	285	254
9	339	10.5	190	288
10	372	10.9	245	272
11	405	11.1	280	220
12	438	11.1	255	222
13	471	11.1	301	292
14	504	11.1	300	230
15	537	11.0	490	292
16	570	11.0	225	217
17	603	10.9	240	236
18	636	11.3	650	>320
19	609	11.4	750	---
20	702	11.5	2100	---
21	719	10.9	4700	---
22	725	10.7	890	---
23	731	11.3	7000	---

Average mud weight using all samples - 11.1

Shear strength averaged for samples 3 through 7 - 260 lbs/100 ft^2

Average gel strength of samples 3 through 7 - 267 lbs/100 ft^2

APPENDIX 4-16

Appendix 4-16

Report of Examination of Mud Conditions (AIC, 1988)

October 6, 1988

Mr. James Clark
E. I. Du Pont de Nemours and Company, Inc.
P. O. Box 3269, Mail Area 83
Beaumont, Texas 77704

In re: Mud conditions of reentered wells

Dear Sir,

Agency Information Consultants, Inc. (AIC) has researched the files of the Texas Railroad Commission (TRC) to identify oil and gas wells that have been reentered within the past two years. The objective was to identify wells that had been originally drilled and plugged within the past twenty to thirty years to determine the condition of the mud in these wells upon their reentry.

From the Texas Railroad Commission files, AIC identified wells that had "reentry" permits filed in 1987 and 1988. AIC then contacted the operators of these permits to determine if reentry had occurred and to ask the condition of the mud. If a well had been reentered, AIC requested any documentation or verbal comment that might be available as to the condition of the mud. For wells that had been reentered AIC also retrieved the well's original plugging records from the TRC to indicate when and how the well had been plugged.

A summary of AIC's interviews and accompanying well records is found in the attached report entitled "Report of Examination of Mud Conditions.

Sincerely,

Rickye Lennon

Attachment

RLL/rad

REPORT OF

EXAMINATION OF

MUD CONDITIONS

Agency Information Consultants, Inc. (AIC) examined the 1987 & 1988 drilling permit indexes for operators who have filed re-entry permits in the Gulf Coast Area and West Texas. The Texas Railroad Commission files were researched for the wells actually re-entered. The operators were contacted, but many unable to provide information. The operators in the Gulf Coast Area that were able to provide AIC with information found the mud to be hard, but the operators in West Texas found it to be soft. The majority of the operators stated the top of the mud was just below the surface plug, but did not know the exact depth.

AIC contacted Louis A. Newitt, who over the past five years has been re-entering wells in the Gulf Coast Area. The last ten to fifteen wells he has re-entered have had casing left in the hole and both cement and mud were used to plug the wells. Mr. Newitt said from his experience mud sets up like cement and the only way he has been able to tell the difference between the mud and cement is by the color. He also stated mud sets up firm after about five years.

Mr. Pat Ray with Famcor Oil, Inc. was contacted about the Langham Unit #1 in San Jacinto County which was plugged as a dry hole on January 29, 1966 (See Exhibit A-1). Ray could only remember the mud was hard and it took a long time to drill through the plug.

AIC spoke to an engineer with Hughes Texas Petroleum Ltd. in Beeville, Texas. He said the mud in the Gulf Coast Area is usually dehydrated and hard. The top of the mud drops down to approximately one hundred to two hundred feet.

Mr. Jerry Cheatham with Jerry Cheatham Operating Inc. said most of the wells he has re-entered in the Gulf Coast Area have to be conditioned before drilling through the plugs because the mud is so hard and firm. Mr. Cheatham also said the mud was at the surface.

AIC contacted Mr. David Russell with John McGown and he stated "most of the fluid is in suspension. The water is on top with mud particles on the bottom." Mr. Russell also said the top of the mud is usually below the top cement plug.

AIC contacted Enerquest Petroleum, Inc. and was referred to Mr. Ken Patterson about the H. E. Evans #1 in Coleman County which was plugged as a dry hole May 31, 1956 (See Exhibit B-1). Mr. Patterson stated the mud was soft and a little dehydrated, but in good condition. The only plug was a five sack cement plug at the surface and then the hole was full of mud. Mr. Patterson did not know the depth of the top of the mud.

Russ with Harken Production Company in Abilene, Texas was contacted by AIC. He re-entered a dry hole in Taylor County known as the Ella P. Edins #1 (See Exhibit C-1). Russ said cement plugs were found at the surface and at one hundred feet and another one at approximately three thousand feet. The hole was full of mud and the mud was like jello with a grey tint to it. He felt the mud was in good condition at the time the well was re-entered.

AIC spoke with Mr. Jack Fisher about a couple of wells he re-entered in Jones County which were originally plugged in 1960 (See Exhibit D-1). Mr. Fisher said the mud was hard, but he was unable to determine the top of the mud.

Crump Petroleum Corporation was contacted about the re-entering of the T. B. Rutherford #1 in Stonewall County which was plugged April 6, 1955 (See Exhibit E-1). The mud was soft, but he did not know the depth of the top of the mud. The well was plugged with cement and mud.

AIC, also contacted Mr. Greg Norman with Gunn Oil Company about the re-entry of Tom L. Burnett #1 in Foard County which was plugged as a dry hole May 31, 1945 (See Exhibit F-1). Mr. Norman stated the mud was in good condition. The mud weight was 9.7 at the top of the mud. The well had a cement plug at the surface and fifteen hundred feet of surface casing left in the hole.

The following companies which were contacted use state funds to replug old leaking wells in West Texas.

AIC contacted Mr. Lynn Smith with X-Cel Well Service & Drilling about the mud conditions. He said most of the leaking wells he replugs were originally plugged with mud prior to 1940. Mr. Smith was unable to give AIC any additional information.

Battista Drilling was contacted and the wells are usually plugged with mud, pipe, and iron. He said these wells are leaking due to injection pressure. The mud is soft and at the surface. He also stated the top of the mud for wells not leaking is usually at one hundred feet or less in West Texas.

AIC contacted Riffe Drilling Company and the wells they plug are usually flowing salt water and are originally plugged with mud in the 1920's. The top of the mud varies, but it is usually around one hundred feet.

Bill with Yellow Mound Oil Company stated that the majority of wells he replugs were cable tool wells drilled in the 1920's. When replugging the wells he usually finds a mesquite or oak plug with soft mud in the hole.

EXHIBIT A-1